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E ORDENAMENTO DO TERRITÓRIO

Coral Bleaching: A Maldives Case Study
Understanding Coral Reefs by using Remote Sensing in the Ari Atoll

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[Porto, 2024]

[Ashwin Kumar]

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Abstract

To understand how coral ecosystems function without conducting in situ research, we utilize satellite imagery. In this study, coral bleaching was monitored using optical remote sensing by employing sentinel 2 imagery. Sentinel provides one of the closest spatial resolutions (10m) to observe coral ecosystems over a large area. Five islands in the Maldives were selected based on the environment and coral bleaching activity. This data was then compared with changes in sea surface temperatures and chlorophyll data to establish a pattern and understand the cause. The results showed coral bleaching on an optical database which was then classified into 3 distinct categories (light coral bleaching, medium coral bleaching and strong coral bleaching) that was compared and studied with previous research done in this field.

Key-words: Coral Bleaching, Coral Reef, Sentinel 2, Chlorophyll, Temperature

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1. Introduction

1.1 What are coral reefs?

Coral reefs are composed of colonies of tiny individual corals called polyps, which are marine invertebrates made of calcium carbonate and are permanently fixed in place (sessile). These reefs provide food and shelter to a variety of marine life, including fish, molluscs, and sponges. The most biologically diverse coral reefs in the world are located in the Coral Triangle region of Southeast Asia (*Natural History Museum*). The most accurate response of corals to environmental stress is to expel their symbiotic dinoflagellates known as zooxanthellae from their tissues into the environment during which is called as Coral Bleaching (*Lesser et al, 2011*).

Within these coral ecosystems, protozoan dinoflagellates of the family Symbiodiniaceae, known as zooxanthellae, play a crucial role. These diverse, mostly symbiotic, unicellular algae are found in marine invertebrates such as corals, molluscs, and sponges (*Torres et al., 2021*).

Corals are completely dependent on symbiotic algae, specifically zooxanthellae, for their survival. In this symbiotic relationship, the host coral provides shelter and inorganic nutrients to the zooxanthellae. In return, the algae assimilate these nutrients and export high concentrations of oxygen back to the coral (Figure 1), which are essential for calcification and other metabolic processes (*Muscatine, 1990; Yellowlees et al., 2008; Davy et al., 2012; Fransolet et al., 2012*).

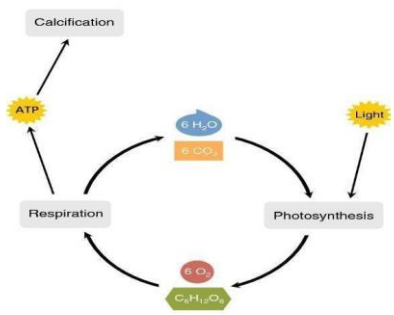


Figure 1 - Process of coral reef formation (Nelson et al, 2019).

Corals have the ability to regulate the quantity of algae living within their cell tissues by controlling the amount of waste that supports algal growth or by adjusting light exposure. They achieve this by opening or closing their polyps to regulate the light as needed. These algae are sensitive to low salinity levels and thrive in temperatures above 20°C.

Functional groups (*Bellwood et al, 2004*) perform ecological roles within the coral reef system. Bioeroders: These species consume dead corals and provide a new settlement for coral and algal species. Grazers: Fish reduce the coral overgrowth by consuming competing macroalgae providing a balance to the ecosystem Scrapers: They remove the algae and other sediments facilitating the growth of coralline algae

1.2 What is coral Bleaching?

Corals are animals that live in a symbiotic relationship with tiny algae called zooxanthellae. Under stressful conditions, such as changes in temperature or pollution, corals expel these algae, causing them to lose their colour and turn white, a phenomenon known as coral bleaching.

According to the Global Coral Reef Monitoring Network's, "Status of Coral Reefs of the World: 2020" report, there has been a steady decline in hard coral cover since 2010. The most severe impacts have been observed in South Asia, Australia, the Pacific, East Asia, the Western Indian Ocean, the Gulf, and the Gulf of Oman. By 2034, it is expected that severe bleaching will occur annually, making recovery nearly impossible unless corals adapt to higher temperatures (GCRMN).

From 1998 to 2017, coral bleaching was particularly common in areas experiencing high-intensity thermal stress anomalies. Bleaching events were more frequent in mid-latitude sites compared to equatorial regions. From 1998 to 2017, coral bleaching was very common in areas with high intensity thermal stress anomalies showing higher frequency of bleaching in mid latitude sites as compared to equatorial sites (*Sully et al, 2019*).

Global coral reef decline necessitates improved management practices. Overfishing, pollution, disease, and climate change threaten these vital ecosystems. While specific coral and reef fish groups maintain the symbiotic balance (*Bellwood et al., 2004*), current monitoring methods offer a limited perspective. Coral coverage, a common metric, provides localized data, failing to capture global reef health (*Madin et al., 2015*). The frequency of coral bleaching thermal stress increased to Three-fold between 1985-91 and 2006 to 2012 and over one third of the world's corals were exposed to bleaching stress more than twice per decade (*Heron et al, 2016*).

1.3 What causes coral bleaching?

Overfishing and the use of destructive means such as explosives, poisons and reef gleaning can directly damage coral reefs. These threats affect high-value species that depend on the reef for food such as snappers, sharks and lobsters. Furthermore, coastal development such as human settlements, industry and infrastructure along coastal zones can affect coral reefs through damage via dredging or land filling. There have been significant global coral bleaching events since 1998 with spikes observed in 2010 and 2014 up until 2017 (*Oliver et al, 2018*).

Increased concentrations of greenhouse gases in the atmosphere have led to the warming of the atmosphere and as a result led to rising sea surface temperatures. This change causes the corals to lose their colourful symbiotic algae leading to white skeletons. Corals are highly susceptible to changes in temperature and can die if the heat stress is prolonged. The change in CO_2 concentration in seawater leading to ocean acidification, decreases the pH of the ocean making it more acidic and decreasing the availability of aragonite which forms the main structure of calcium carbonate that corals use to build their skeletal structure. Coral Calcification is significantly reduced when seawater becomes slightly acidified, primarily due to changes in the CO_3^{2-} concentration (*Erez et al, 2011*). In addition, warming ocean temperatures are increasing the frequency of the strongest tropical cyclones that contribute to high waves which damage many coral reef communities. Major bleaching events are also connected with strong El Niño events (*Oliver et al, 2018*).

In 1989, Lesser and Which conducted culture-based experiments exposing zooxanthellae to ultraviolet radiation (UVR) that caused a decrease in photosynthetic pigments thereby lowering the growth rates and causing a general decrease in carbon fixation. This resulted in the oxidative stress that leads to the production of Reactive Oxygen Species (ROS), damaging the corals at the cellular level and triggering a process like apoptosis and necrosis (cell mortality). The presence of the species can overwhelm the defensive capabilities of the coral reef leading to cellular damage, thereby affecting coral health. Corals show reduced photosynthetic and calcification rates when subject to hypoxia and hyperoxia (*Nelson et al., 2019*).

1.4 Coral Bleaching Observed Around the world

Australia: The Great Barrier Reef across the east coast of Australia has the world's largest area of coral reef ecosystems and therefore has been subjected to many research studies related to coral bleaching. Corals have developed thermal tolerance through sub bleaching stress events which have reduced the cell mortality and symbiont loss in this region (*Ainsworth et al, 2016)*. Future climate change conditions predict that small changes in local temperatures could eliminate this protective mechanism which would lead to a more severe bleaching event and the further degradation of coral reefs in the Great barrier reef. It is significantly impacted by sediments and toxicants during the rainy season (*Devlin et al, 2015*). Queensland and the Australian government are protecting the reef area through various land management practices and coastal monitoring programs.

India: Coral reefs are present on both sides of the Indian subcontinent, i.e. the Arabian Sea (Lakshadweep islands) and the Bay of Bengal (Andaman and Nicobar Islands). Coral bleaching was recorded during 1997 during the ENSO event (*Arthur, 2000*). The Gulf of Kutch (Gujrat, Northwestern India) showed minimal bleaching while Lakshadweep and the Gulf of Mannar (Tamil Nadu, Southeastern India) experienced severe bleaching events leading to coral mortality. A study in Lakshadweep showed that higher levels of NO_2 and NO_3 in Kavaratti and Agatti islands were noticed contributing to coral stress. Varying Sea surface temperatures and pH were the main factors contributing to coral bleaching in this region (*Kumaresan et al, 2018*).

Southern Atlantic Reefs: The reefs present in the Southern Atlantic region are susceptible to a phenomenon called El Nino that is a recurrent, quasi-periodic appearance of warm sea surface water in the central equatorial Pacific Ocean generated by ocean-atmosphere interactions internal to the tropical Pacific and overlying atmosphere (*Santos, 2006*). These reefs have shown certain unique features making them less susceptible to mass bleaching as compared to the Indo-Pacific reefs (*Miles et al, 2020*). Contrary to the above studies, the Brazilian reefs in marine protected areas such as Parque Estadual Marinho da Pedra da Risca do Meio located 23km from Fortaleza city highlights a major bleaching event in 2010 due to the various SST anomalies of temperatures increasing from 1 to 1.7°C causing heat stress in corals (*de Oliveira Soares et al, 2019*).

1.5 Sources to Detect Coral Bleaching.

Allen coral atlas: This website provides locations where coral reefs are present in shape files and satellite imagery from 2018 to 2020. It also provides the benthic map of a given area which determines the type of life, and other geological features found in the area. The most significant tool used is Coral reef bleaching (Beta), which shows the area bleaching alert areas from NOAA data. They are demarcated in green for certain regions across the globe on specific dates. It combines satellite imagery data with ecological information about the local area and provides a reef map. A study by Kennedy et al in 2021 across the Great Barrier Reef and Mariana islands monitored coral reefs using Allen Coral Atlas for conservation and management strategies with help from Landsat 8.

Coral Reef Watch: Created by the National Oceanic Atmospheric Administration (NOAA) in 2000 by the United States, Coral Reef Watch provides a vast amount of data dealing with the sea surface temperature, various coral reef zones and other relevant data from 1980 to the current year (Figure 2). This information is obtained in Satellite images from specific annual or seasonal durations in NetCDF4 format.
This image describes the different alert levels issued by the CRW community indicated by various colours. For the corals of Maldives, we can see that it has been on "Watch"

status indicated in yellow. Since its inception, the CRW 5 km DSS has monitored thermal stress globally and identified reef locations at risk of bleaching (*Heron et al, 2016*). The NOAA bleaching outlook system covers the tropical latitudes between 30°S and 30°N. The outlook comprises three integrated parts: sea surface temperature (SST) prediction model, coral bleaching thermal stress prediction, and coral bleaching outlook (*Liu et al, 2008*)

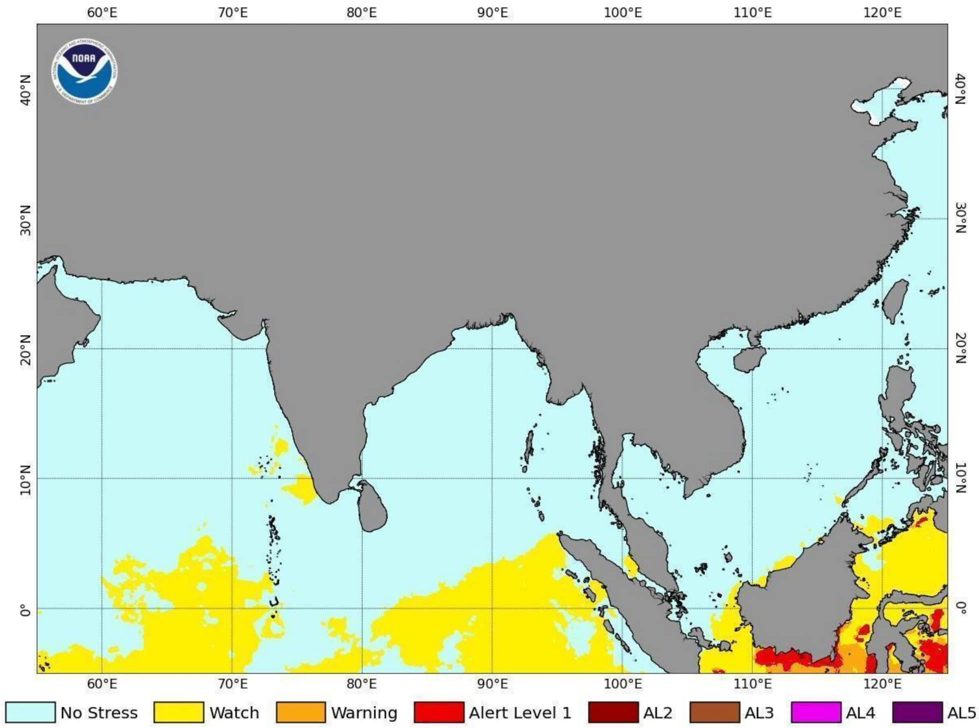


Figure 2 - NOAA Coral Reef watch of the Indian Ocean for January 1, 2024 (NOAA CRW).

<u>Sentinel 2 Data:</u> Unlike the data from Allen coral atlas and CRW, Sentinel 2 Data must be processed to generate coral bleaching of a particular area. To make a detailed procedure concise, the data is selected from Copernicus dataspace and is then processed in the Sentinel Application Program using the sen2cor plugin. This data can then be observed using ArcGIS pro as shown. By optical remote sensing, we can visualise the corals being bleached from 2017 to 2024 (Figure 3). Compared to SPOT-4 and Landsat, differences in sensor band configurations and benthic reflectance from the ocean it provides a higher and more reliable process for coral reef monitoring. It's design features such as narrow

bands and increased spatial resolution contributes to this enhanced capability (*Hedley et al*, 2012).

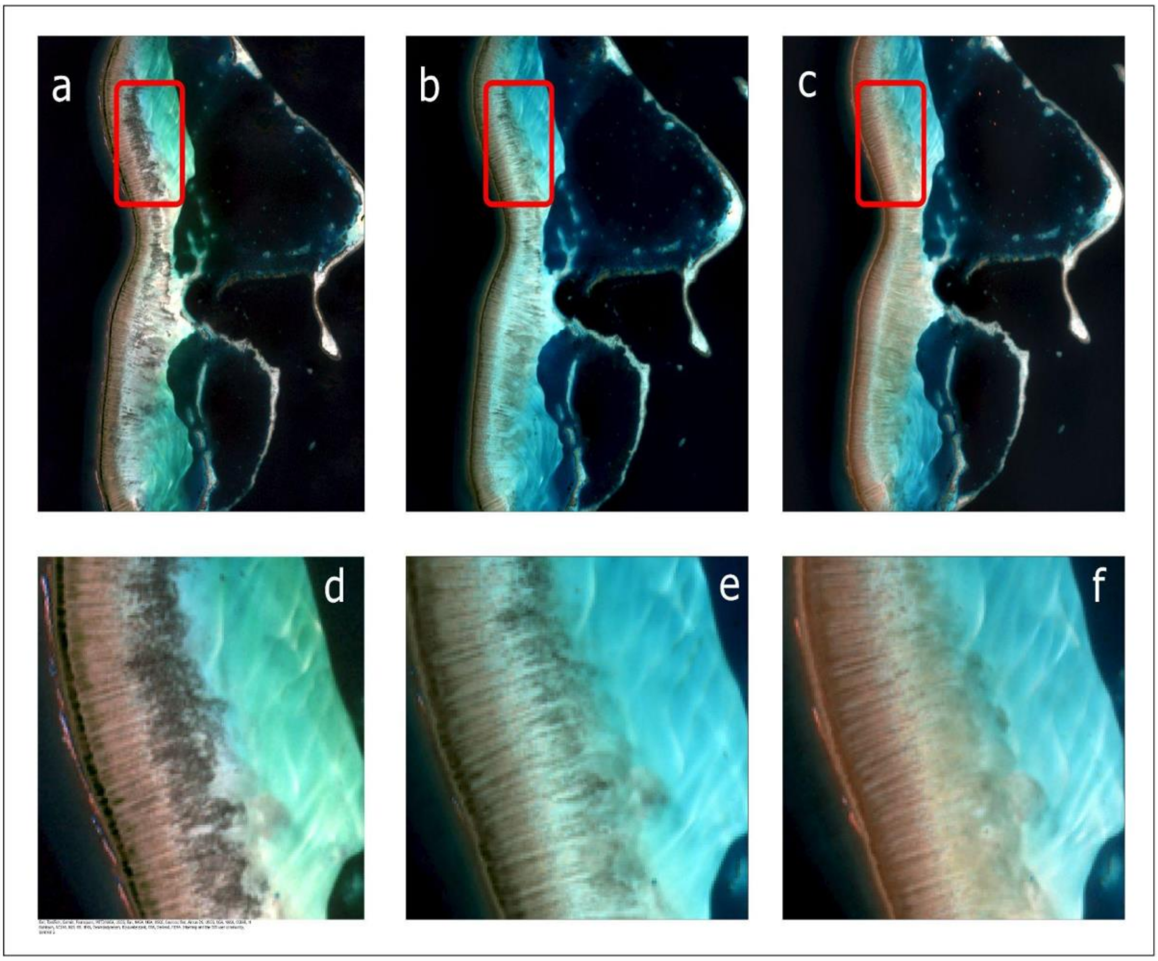


Figure 3 - (a,b,c); Corals in the Maldives in 2017, 2020 and 2024 respectively obtained from Sentinel 2 and Processed by SNAP). (d,e,f); Visual Coral Bleaching in the Maldives in 2017, 2020 and 2024 marked in red.

2. Review of Literature

2.1 Studying Coral bleaching through the lens of a satellite

The use of satellite information in the past few decades has increased as this data can be observed over areas that may not be accessible or economically practical to conduct field work. Satellite and compiled in situ observations of the sea surface temperatures have expanded the ability to detect anomalous conditions and are widely used for studying coral bleaching and mortality. Field observations are needed to confirm the synoptic satellite predictions for reefs where acclimation and reorganization of the coral community have occurred due to past bleaching events (McClanahan et al, 2006).
Sentinel provides one of the closest spatial resolutions (10m) to observe coral ecosystems over a large area.

2.2 Research done in Coral Bleaching (SCOPUS)

Since 1995, there have been over 185 research articles published in Scopus based on Coral Bleaching and Satellite data showing an annual growth of 5% with almost 35% of the papers representing international cooperation and collaboration of research work done in coral bleaching.

Articles Published and Cited

There has been a steady decrease in citations from 1995 with an ever-increasing number of articles published (Figure 4). In the past decade, there has been a very high increase in articles published from 2013 to 2019 showing an increased relevance and consideration to the coral bleaching events as they had become more frequent with over 18 articles written in 2019 making it the highest number of research articles published in just one year since 1994.

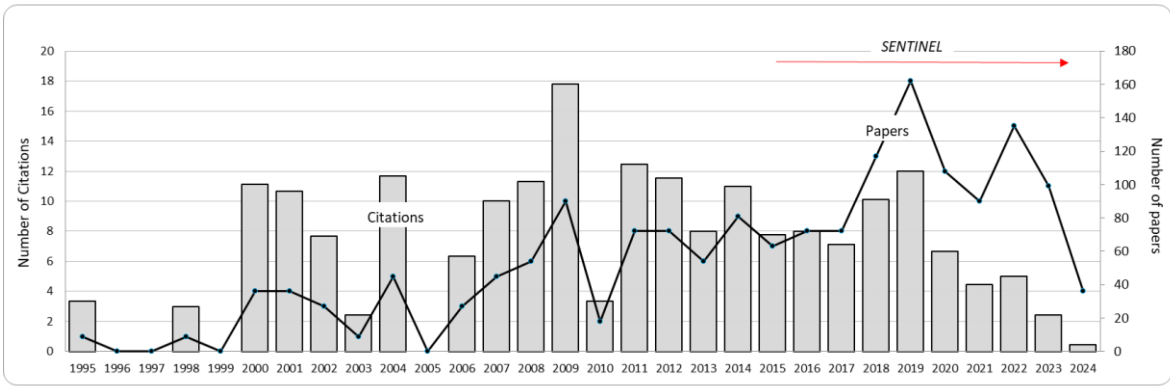


Figure 4 - Articles and Citations in Coral bleaching (SCOPUS)

Most Relevant Authors

Heron SF has 14 articles published in coral bleaching with the highest article showing 343 citations. The highest number of citations recorded in this field is 2053 (Global warming and recurrent mass bleaching of corals) by Hughes TP (2017) in nature with just 1 article published.

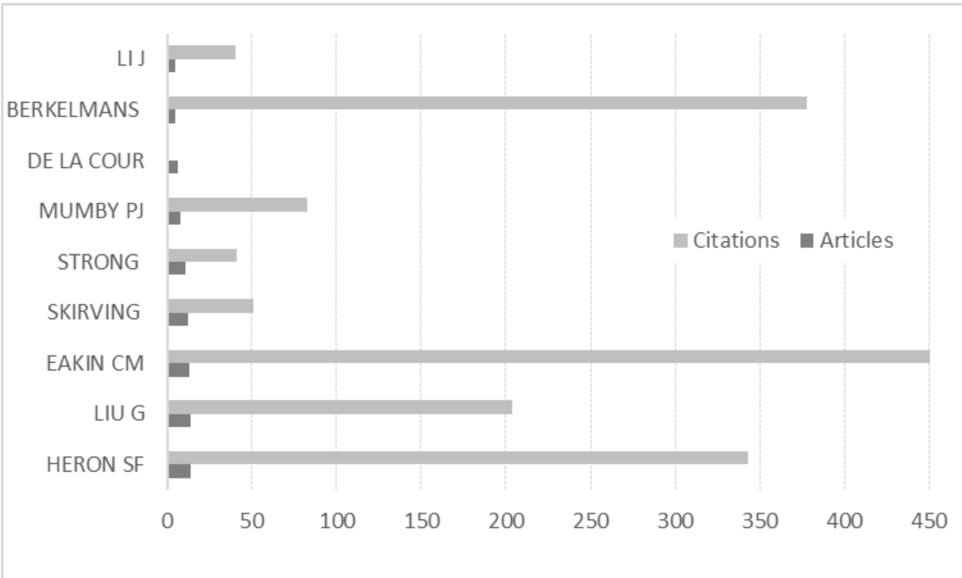


Figure 5 - Articles and citations of relevant authors in Coral Bleaching.

The following author would be Eakin CM with 13 articles (Figure 5) published and over total number of 453 citations in 2010. This graph does not show a steady change in the trend of Articles and Citations of relevant authors in this field as evident with

Berklemans R (2004) with over 378 citations with just 5 articles in the field which proves that there is an almost equal number of articles published by relevant authors with the total number of articles cited by other authors either using it as a base to define the project or to quote a certain observation.

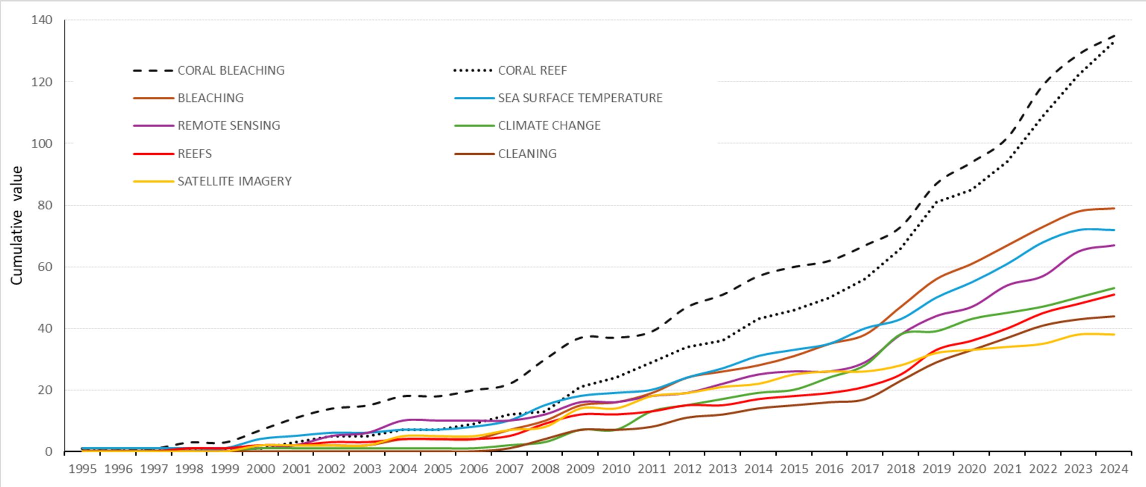


Figure 6 - Cumulative occurrence of words relevant to coral bleaching.

The term Coral Reef has not been an unfamiliar concept ever since 1995, as it was similar with other terms like sea surface temperature and climate change (Figure 6). With change in SST and Climate phenomenon noticed in 2004, there was a sharp increase in the term ‘coral bleaching’ that has always been correlated with coral reefs till the present day of research. With this graph we can understand that Coral bleaching has been studied using remote sensing technology since 2009 and often observed a close relation with the term ‘bleaching’.

Journals Representing Coral bleaching

Coral Reefs (established in 1982) is the official publication of the International Coral Reef Society with over 22 articles related to coral bleaching since 1995 with an impact factor of 3.5 (2022) at rank 1.

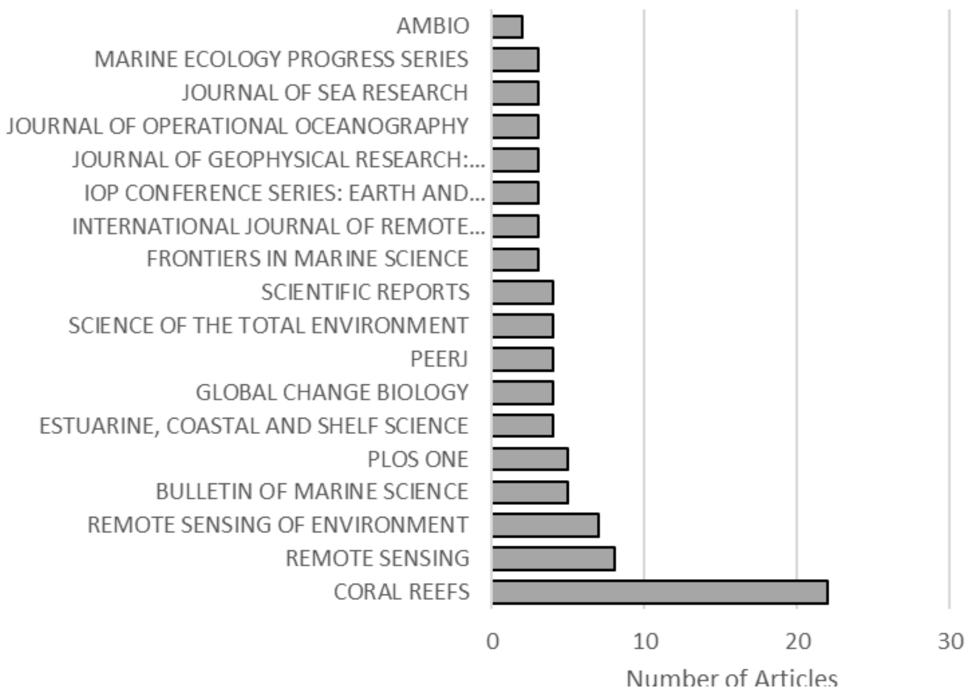


Figure 7 - Journals that published articles related to coral bleaching.

2.3 Research done in Coral Bleaching (Web of Science)

Using web of science, the research completed using satellite data shows 50 documents relevant to coral bleaching with nearly 60% of international cooperation and 140 average citations per document, set aside articles published in Elsevier (SCOPUS).

Articles Published and Cited

Over 22 years, there have been some inconsistencies in the data cited on the web of science with a peak occurring in 2003 of an average of 63 citations, while 2004 showed no citations and a gradual incline till 2021. The number of articles published has been synonymous with the average number of citations with 6 articles published in 2010 having 84 citations. It has been noted from 2009, the total number of articles related to coral bleaching published, significantly increased, and then shows a gradual increase in the research conducted till 2021.

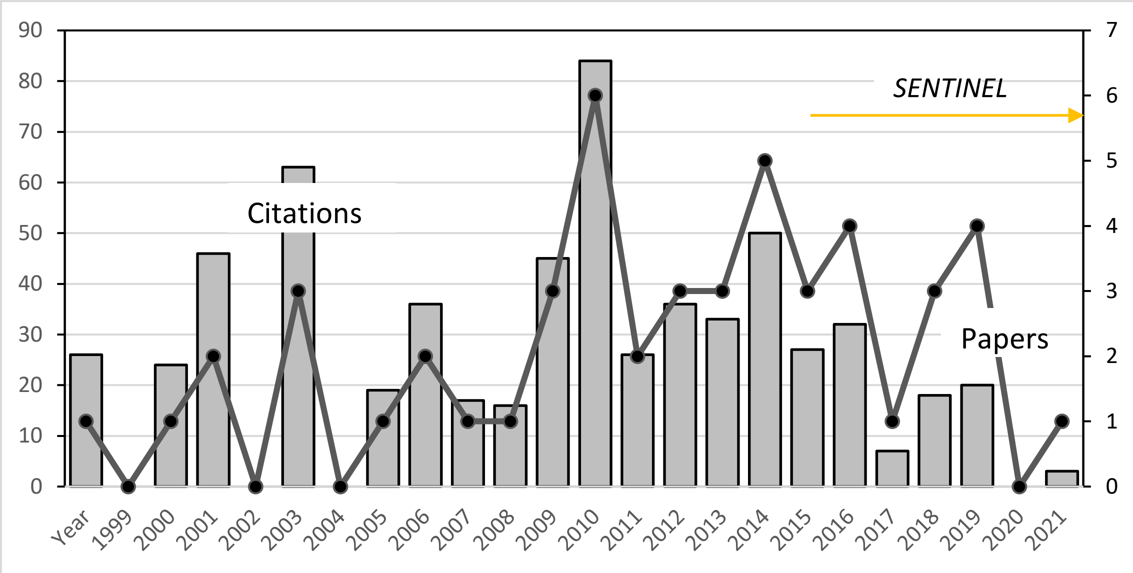


Figure 8 - Graph Showing Articles and Citations in Coral bleaching (Web of Science).

With the availability of sentinel 2 data from 2015, we could speculate that the number of articles published have changed in frequency, as evidenced from 2015, showing a secondary peak at 5 articles published in that year. The relevance and notoriety of coral bleaching has been ever increasing, as seen with the number of articles published in the past decade.

Most Relevant Authors

The data is similar to Scopus with HERON SF having the greatest number of articles (8) and EAKIN CM with the highest number of citations (442). In Addition, McClanahan TR has 203 citations with 4 articles published in reference to Coral bleaching, the most relevant being *Effects of climate and seawater temperature variation on coral bleaching and mortality* published in 2007. HERON SF catalogued warming trends and bleaching stress of the coral reefs across the world from 1985 to 2012. This research serves as a guide to studying coral reefs with respect to changes in temperature caused by global warming.

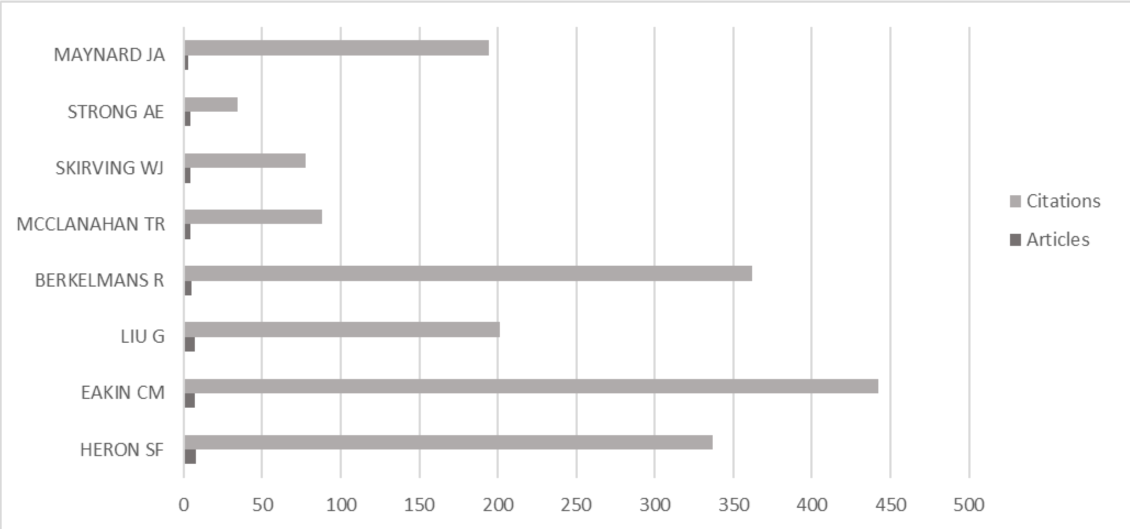


Figure 9 - Graph Showing Articles and citations of relevant authors in Coral Bleaching (Web of Science).

Liu G, Heron SF and Eakin CM are the most cited and most published authors in the field of coral bleaching as they worked together on Reef Stress using data from NOAA Coral Reef Watch as compared from 2013 to 2014. They monitored coral stress in near real time.

Journals Representing Coral bleaching

Coral Reefs has over 10 publications following PLOS ONE with 7 publications.

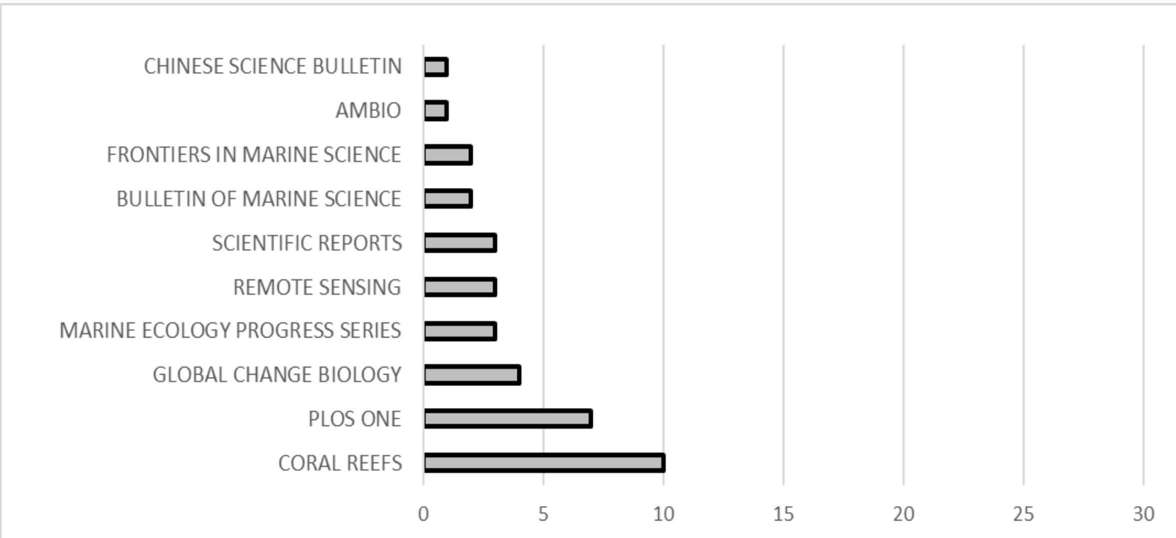


Figure 10 - Journals that published articles related to coral bleaching (Web of Science).

Limitations

Remote sensing estimates the results based on the type of equipment used and the environment of study. In 2003, H. Yamano and M. Tamura observed limitations in coral reefs by data analysis. Using blue and green Landsat TM bands, they noticed bleaching events in 23% of the coral cover and 15% was not detected due to the spatial resolution limitations. Sand interference and spatial variability could hinder the imagery. They proposed that advanced sensors such as IKONOS, ALOS etc. with high resolution and shorter satellite recurrence intervals could enhance the detection of coral reefs.

In 2012, Hedley et al noticed a few Sensor limitations in optical remote sensing of coral reefs. Different benthic types at different depths may be spectrally indistinguishable due to the sub-pixel mixing of benthic areas. Within the scale of a remote sensing image, the change in environment factors such as water clarity, depth etc. cause a variation in the benthic classes as clear water is essential for precise discovery.

By reviewing Coral reef ecosystems using remote sensing Xu et al (2014) observed certain challenges faced in China with the deficiencies in data collection and the use of NOAA AVHRR for monitoring sea surface temperature. Dedicated satellites for studying corals and the limitations of the technology were the main conclusions of this research.

In 2018, S.J. Purkis noted that water turbidity makes it difficult to identify coral reefs submerged below a particular depth. He also observed the qualms of atmospheric distortion and pixel resolution difficulties and cited 'ground truth' observations to study large scale coral reefs.

A study of the spatial distribution of coral bleaching in Hawaii, 2018 by using small unmanned aerial systems showed that wind generated waves can cause distortions at lower altitudes. They concluded that it is important to combine in Situ data with the data provided by the drones to form an accurate output as heterogenous factors such as change in temperature and depth could impact the study and affect the accuracy of the observations.

3. Study area

Maldives is an archipelago located in the Indian Ocean, South Asia, south-southwest of India. It has a total land size of 298 km^2 which makes it the smallest country in Asia. It consists of 1190 coral islands forming 26 atolls (Figure 11) spread across 90,000 km^2. The capital city of Maldives is Malé. Most of the atolls in Maldives consist of ring-shaped coral reefs that have many small islands.

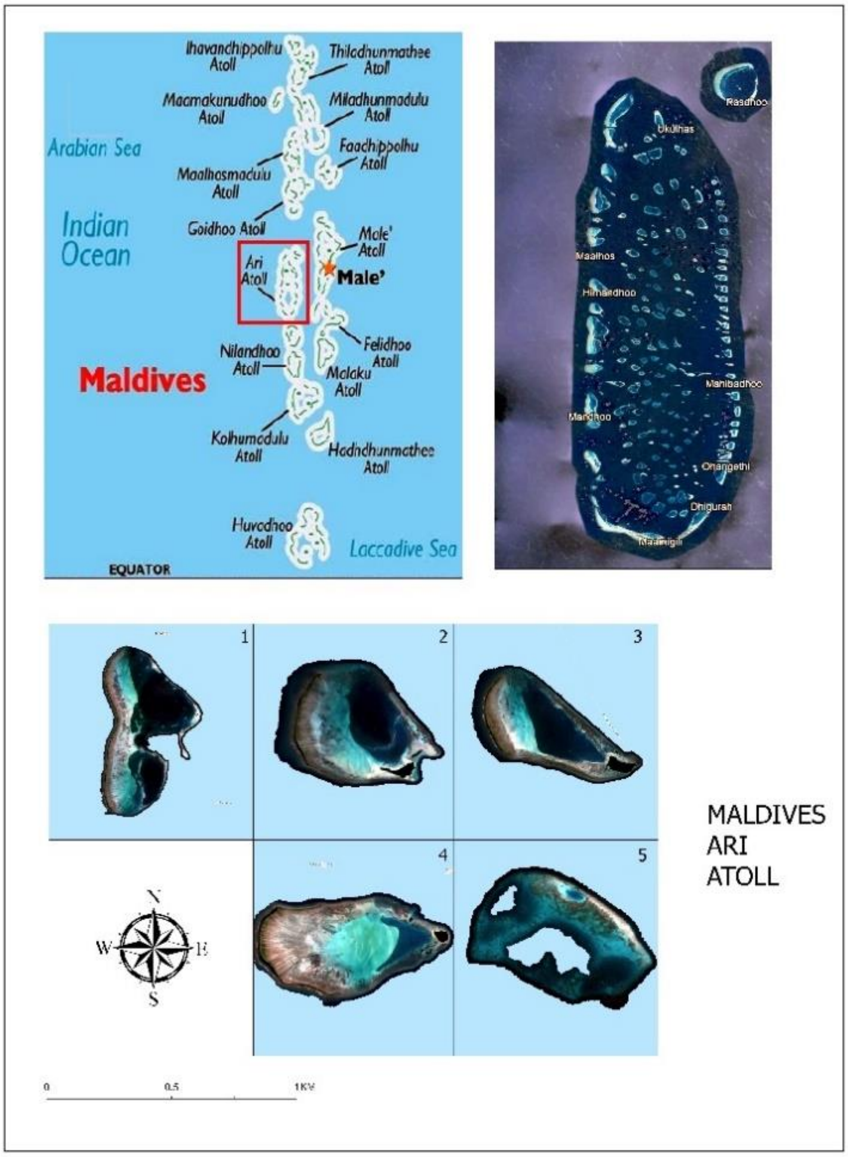


Figure 11 - Study area of the Ari Atoll, Maldives

4. Materials and methods

4.1 Materials

To study Coral bleaching, we need to compare the images showing bleaching patterns with factors that affect coral bleaching such as Temperature and Chlorophyll content. This Methodology is therefore further divided into 3 tasks. This data is then studied in ArcGIS pro. The following pictures displayed for each task are large scale images of the whole region to provide a general understanding of each factor. The study area for each image will be dissected and analysed in the results. Obtaining and processing Coral bleaching Data from Sentinel 2.

4.2 Coral bleaching Methodology

- Acquiring and processing Chlorophyll data from Sentinel 2.
- Obtaining Sea Surface Temperature data from Sentinel 3.

4.2.1 Acquiring the Data

Copernicus Dataspace provides the data from the Sentinel Program. It is available in 2 products, L1C and L2A. The date and time of the data is then selected along with the atmospheric cloud coverage set to ideally, 0 to 5%.

Copernicus Sentinel 2 is a European wide-swath, high resolution and multi spectral imaging program. It consists of 13 spectral bands, 4 bands at 10m, 6 bands at 20m and 3 bands at 60 m spatial resolution. The orbital swath width is about 290 km. It was launched June 23, 2015

Band Number	Central wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)
1	442.7	20	60
2	492.7	65	10
3	559.8	35	10
4	664.6	30	10
5	704.1	14	20
6	740.5	14	20
7	782.8	19	20
8	832.8	105	10
8a	864.7	21	20
9	945.1	19	60
10	1373.5	29	60
11	1613.7	90	20
12	2202.4	174	20

Table 1 - Sentinel 2A Bands.

Sentinel Application Program (SNAP)

SNAP or the Sentinel Application Program is a software that is designed to read and preprocess Sentinel data from all the satellite programs.

Figure 12 - Sentinel Application Program

Once the data is added to the software it is then resampled and reprojected according to the highest bandwidth data with the right geographic coordinate system.

Sen2coral Toolbox

The whole operation of the detection Coral bleaching and preprocessing of the images is carried out with the help of this application. It is a plugin available in the SNAP repository. This tool consists of the following explained in detail below, Deglint, Land and Cloud Mask, Radiometric Normalisation by PIF (Figure 13). Other features include Depth invariant indices to generate a habitat map and Empirical bathymetry to understand the Bathymetry of the ocean floor.

Processing the Data

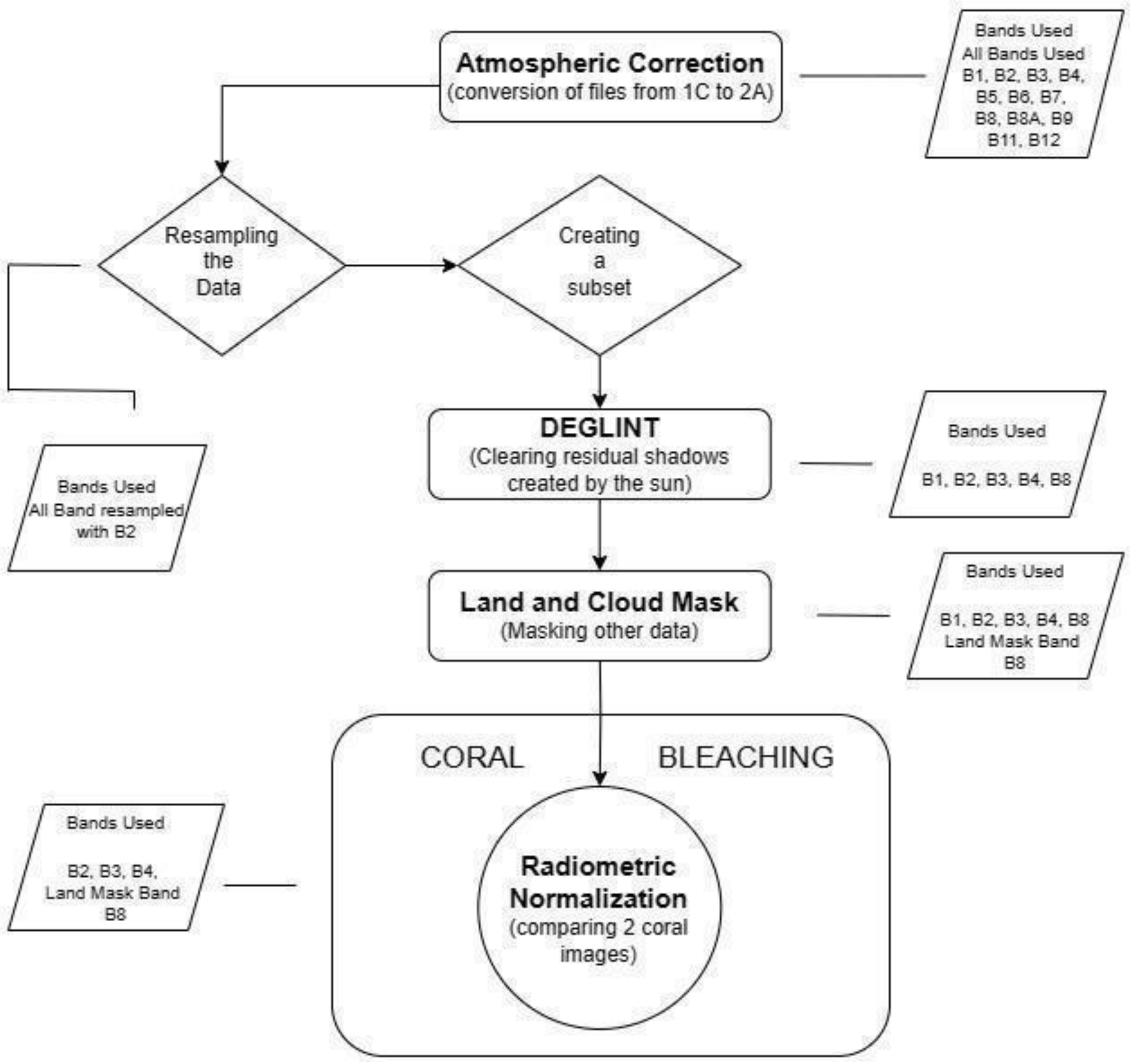


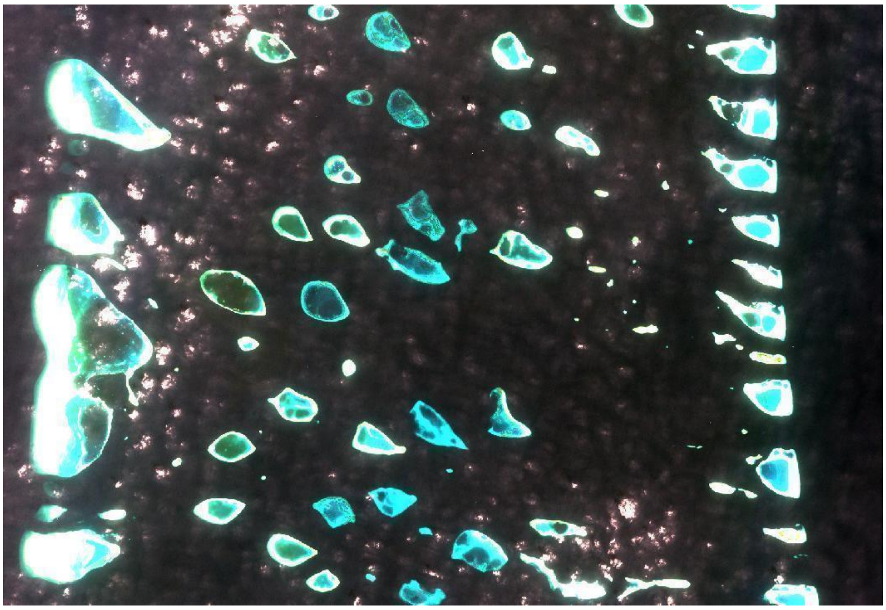
Figure 13 - Process of generating coral reef bleaching in SNAP.

4.2.2 Pre-Processing the Image (Coral Bleaching)

Atmospheric Correction

It is the process of removing the scattering and absorption effects of the atmosphere on the reflectance values of images taken by satellites. According to *D.G. Hadjimitsis (2008),* The objective of atmospheric correction is to determine true surface reflectance (Figure 14 A) values by removing atmospheric effects from satellite images. Part of the brightness is due to the reflectance of the target of interest and the remainder is derived from the brightness of the atmosphere itself.

In SNAP, the SEN2COR toolbox is used for atmospheric correction. The resolution is set at 10m. It takes about 30 minutes (Depending on the system) to generate the results as each band is pre-processed. The files are converted from Level 1C to Level 2A (Figure 14B).



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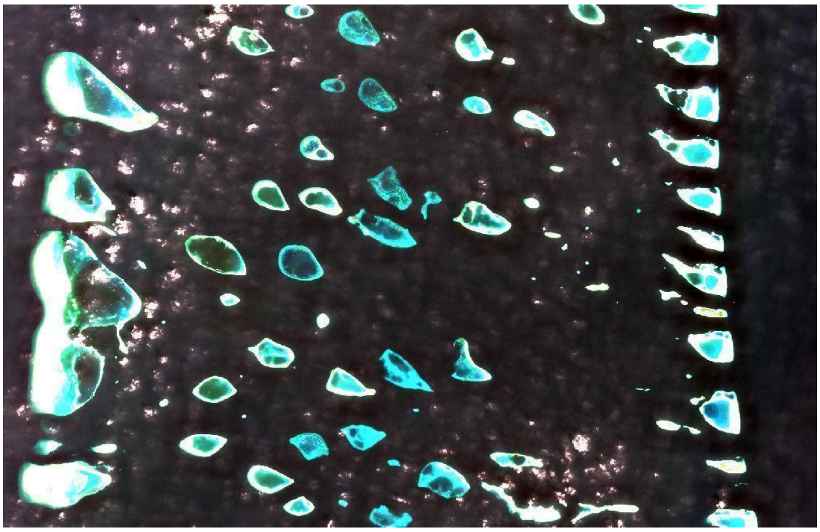


B

Figure 14 - Corals before Atmospheric correction L1C (A); Corals After Atmospheric correction L2A (B).

The 10m resolution file includes spectral bands of 2,3,4,8, True Colour Image (TCI) and an AOT (Aerosol Optical Thickness) map. Band 8a is the reference channel in an atmospheric window region and Band 9 is the measurement in the absorption region. The absorption depth is evaluated with no water vapor assuming that the surface reflectance for the measurement channel is the same for the reference channel. The absorption depth is then a measure of the water vapor column content.
Level 2 products are already available on the Copernicus dataspace website but due to the time range and area of study, Level 1 files must be downloaded and pre-processed as evidence with the above pictures being from 2017 of the Maldives.

Sun Glint Removal (DEGLINT)

It is a pre-processing algorithm to remove the direct reflection of the sun from the air – water interface or 'sun glint'. Brightness in a NIR (Near Infrared) Band is utilised to deglint the visible wavelength bands based on the linear relationships between the NIR and visible bands (*Jingping Xu et al, 2021*). Sun glint is a common phenomenon in satellite images. In the presence of sun glint, we need to apply a glint removal algorithm to observe the ocean floor. Using the sen2cor toolbox, Band 2, 3, 4 and 5 along with reference band 8 is used (Figure 15). This program also requires an input of polygons with the areas highlighted as Sun glint.

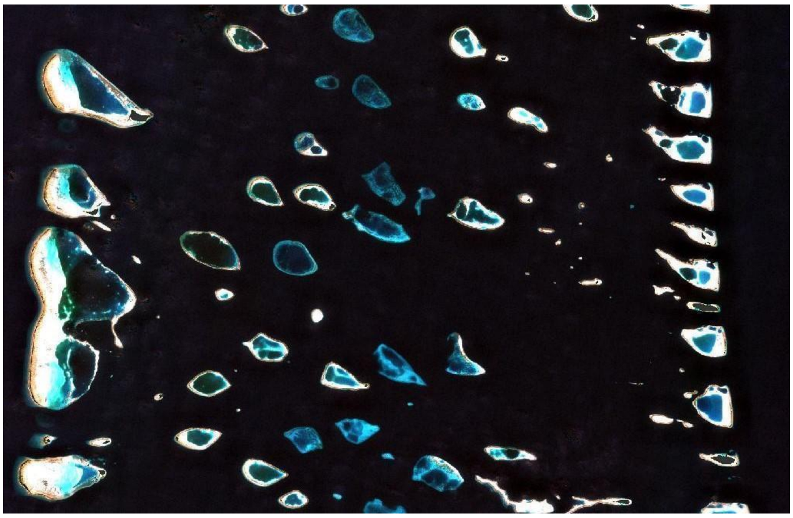


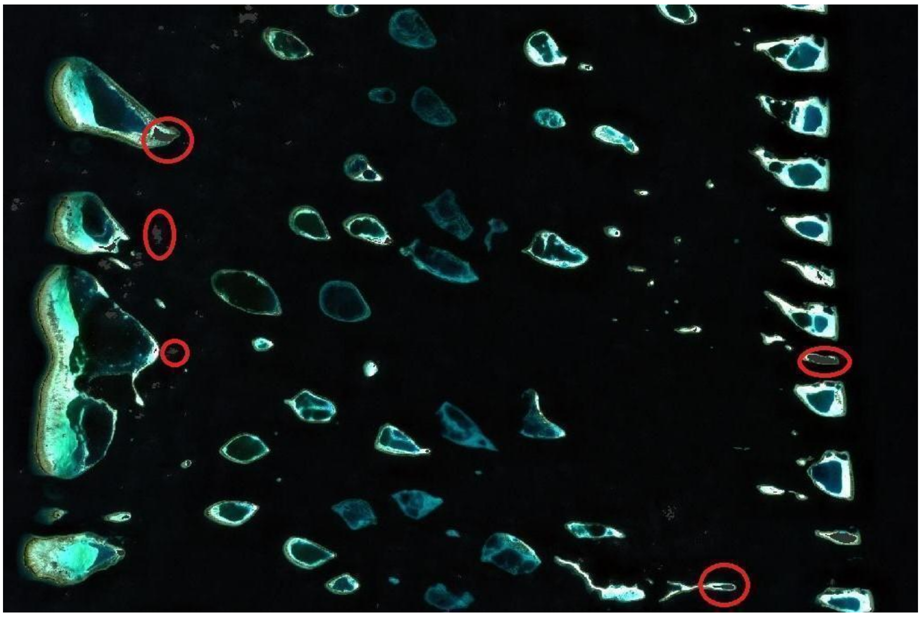
Figure 15 - Deglint applied to Maldives.

As we can notice from the image, the cloud coverage and ocean waves have been removed to form a clear image.

Land and Cloud Mask

This feature creates a layer over areas with white caps, land, cloud, and cloud shadows. Due to their high reflectance, these areas need to be masked.

Expression used: if B2 > 0.01 && LandCloudWhiteCapMask = 1 then 1 else 0



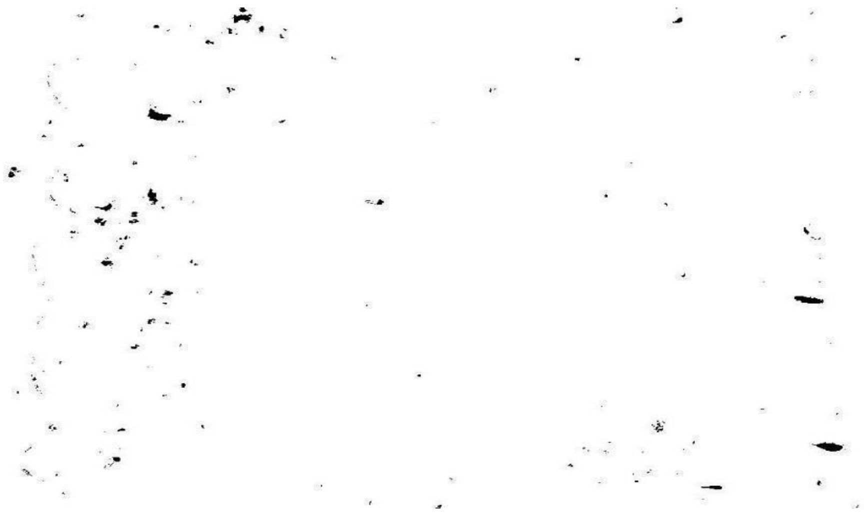


Figure 16 - Masked areas marked in red (A); Band 8 showing the masked areas (B).

4.2.3 Radiometric Normalisation (Coral Bleaching)

It attempts to normalise the radiometric distortion caused by non-land-surface-related factors such as different atmospheric conditions at image acquisition time and sensor and to improve the radiometric consistency (Figure 16) between remote sensing images *(Wu et al, 2018*). It establishes the mapping relationship of radiometric features between different images and can obtain an application of absolute radiometric calibration.

Radiometric Normalisation using (Pseudo-Invariant Features) PIFs

This tool in SNAP helps us to utilise radiometric normalisation to imagery values to the same surface areas comparable throughout a time series. It corresponds to the optically bright or dark areas such as sand and deep-water regions. Maintaining radiometric precision in orbital images is difficult due to factors like Earth-Sun distance and detector calibration (*de Carvalho Júnior et al, 2013*).

This too utilises Band 1, 2, 3, 4 and 5 with PIF rectangles drawn on the map with bright or dark regions. A reference product is first used by which the secondary product is then compared. However, this method faces challenges with heterogenous aerosol scattering and water vapor content (*de Carvalho Júnior et al, 2013*).

Figure 17 - Original processed image from 2017 of Corals in the Maldives (A); Radiometrically Normalised image from 2024 of Corals in the Maldives (B).

As we can notice (Figure 17 B), the coral reefs along the island are highlighted in the normalised image and it shows that a significant number of corals have been degraded over the past 7 years.

4.3 Chlorophyll Methodology

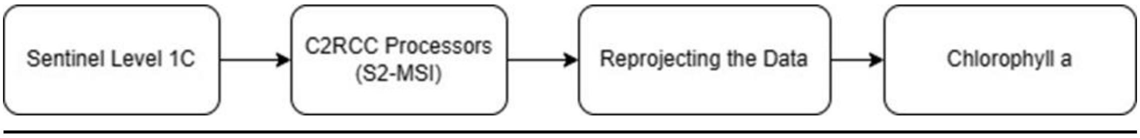


Figure 18 - Flowchart for generating chlorophyll concentration in SNAP.

4.3.1 C2RCC Processors (Case 2 Regional Coast Color)

It is an open-source plugin that uses neural networks which are trained for top – of – atmosphere reflectance to generate atmospheric correction. It relies on a large database of simulated water leaving reflectance and is used to generate an array of results among which includes salinity, phytoplankton pigments (Figure 19), total suspended matter, and chlorophyll content. This tool supports data from MODIS and VIIRS as well. A study conducted in 2019 by Kyryliuk et al showed that chlorophyll had a substantial improvement using CR2CC sentinel 3 sensor as compared to the Medium Resolution Imaging Spectrometer (MERIS) with higher values which ranged from 1.1 to 28.5μ^{-1}.

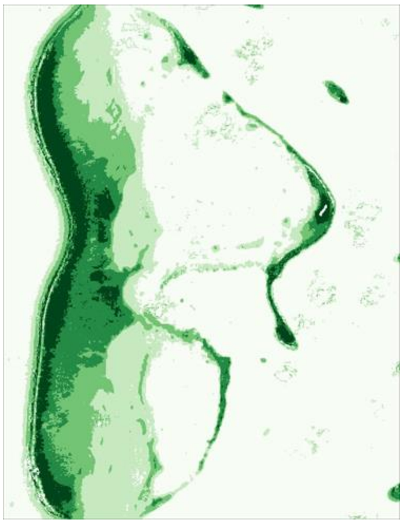


Figure 19 - Chlorophyll concentration of Island 1, Maldives (2017) obtained from C2RCC.

4.3.2 Reprojecting the Data

In order for the data to be projected in the right coordinate system, it has to be reprojected from the original geographic coordinate system to a projected coordinate system. For Maldives, the projected Coordinate Reference System (CRS) would be *Geographic Lat/Lon (WGS84).*

The chlorophyll concentration can be studied for different parts of the coast along the various islands of Maldives which will be discussed in the results.

4.4 Temperature Methodology

4.4.1 Reproject the data

Like chlorophyll, the data is reprojected to the current geographic coordinate system as observed in figure 20.

Subset

A subset of the original data is created where just the temperature of a particular region is taken as the data downloaded from Copernicus displays the whole swath of the earth.

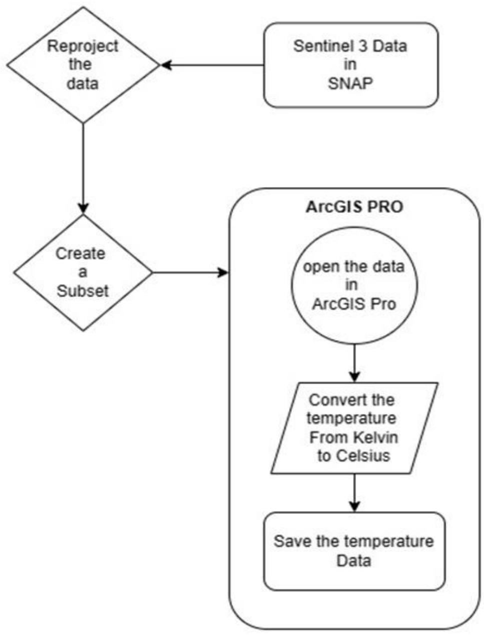


Figure 20 - Flowchart for generating Temperature data.

Sentinel 3

Sentinel 3 is a low orbit satellite designed for a 7-year operational lifetime. It was launched on February 16, 2016.The main objective of sentinel 3 is to measure the sea and land surface area and temperatures with high accuracy. It is operated by the Copernicus data space program. It consists of 4 main instruments. The spatial resolution is 500m for a defined area.

OLCI: Ocean and Land Color Instrument

SLSTR: Sea and Land Surface Temperature Instrument

SRAL: SAR Radar Altimeter

MWR: Microwave Radiometer

The SLSTR instrument is used for obtaining sea surface temperature.

4.4.2 Processing the data in ArcGIS Pro

Raster Functions (Unit Conversion)

The unit conversion feature in Raster functions converts any form of scientific data to a particular value. For this study, the temperature data was converted from Kelvin to Celsius. This data is then resampled to 10m (Figure 21) spatial resolution to study the temperatures on a level similar to the chlorophyll concentration and the classification of the land data.

Figure 21 - Map of Sea Surface Temperature of Maldives.

4.5 Quantification of the data through image classification

Image classification refers to the process of allocating specific classes to a defined land cover system.

4.5.1 Segmentation

The neighbouring pixels are aggregated together to create different levels in the image.

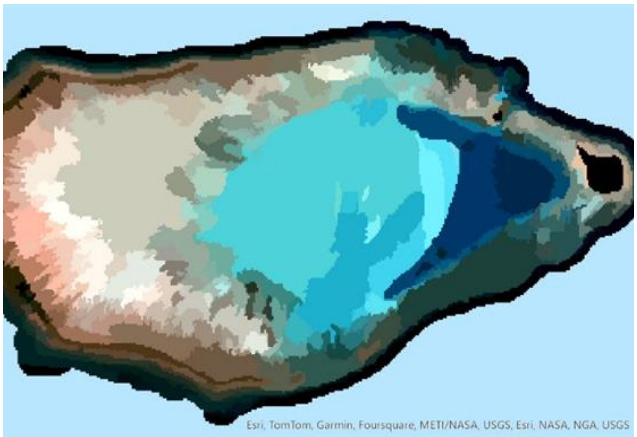


Figure 22 - Segmented image of island 4, Maldives and training Sample created for the classification of Corals.

4.5.2 Training Sample Manager

This tool allows the user to create divisions for each segmented category in the image based on the type of classification warranted for the area. These training samples (Table 2) are transferred to the classifier generally in the middle of the data to find an average between the first and last data points. For the case of Maldives, the training manager is tuned to the data of 2020 due to the presence of mild and critical bleaching values.

4.5.3 Classification

The classification tool provides a choice between a supervised and an unsupervised classification. Based on the availability and type of data, we select a supervised classification that relies on training samples designed for a particular type of ecosystem (Figure 23) as mentioned above.

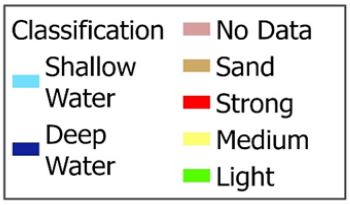


Table 2 - Training Sample created for the classification of Corals

Maximum likelihood classifier

This type of classification is based on 2 principles, the pixels in each sample class and the theorem of decision making. All the segment attributes are selected to generate a compact image.

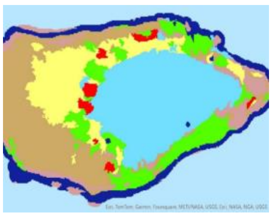


Figure 23 - Classified image of island 4, Maldives.

5. Results

To understand and obtain the results, there must be a strong case for the potential of coral bleaching in generalized areas studied by previous authors and researchers.
In 2016, Heron et al worked on the warming trends and bleaching stress of the World's coral reefs from 1985 to 2012 using satellite data (NOAA pathfinder ~4km) for recording Sea Surface temperatures. Data was studied over a span of weeks (Degree Heating Weeks). DHW of 4°C was used to study temperature conditions as an indicator for coral bleaching and DHW of 8°C was used as a critical point for identifying the mortality levels of the coral reef.

In 2017, Hughes et al studied global warming and recurrent mass bleaching of corals along the great barrier reef in Australia in 1998, 2002 and 2016. Chlorophyll-a was used as an indicator of water quality and the presence of phytoplankton in the water that influenced nutrient levels. They analyzed the varying effects of chlorophyll on the severity of coral bleaching, concurrently trying to prove if low levels of chlorophyll might result in resistance to bleaching. They concluded that chlorophyll-a levels were significant to the study but small in impact as compared to the Degree of heating (DHW) measured in the previous research. The satellite data used was from NOAA Coral Reef Watch (~5km).

According to Fitt. et al (2001) chlorophyll levels serve as key indicator factors to determine the well-being of coral reefs. During times of thermal stress, corals show a decline in chlorophyll concentration thereby quantifying the severity of coral bleaching. The decline in chlorophyll levels serves as a measure in the symbiotic relationship between corals and zooxanthellae due to changing temperature patterns.

5.1 ISLAND 1

5.1.1 Land Classification

In 2017, shallow water dominated the area for land classification as a large portion of this region was submerged at a relatively small depth with almost 20 km^2 at 54%. The deep-water region accounted for 22% at 8km^2. Land region covered up to 0.7km^2 representing 1.94% (Figure 24). Light coral bleaching areas covered up to 0.73km^2, accounting for 2% of the total area. Medium and strong coral bleaching (Figure 27) represented a span of 2.34 km^2 and 1.5 km^2 showing 6.4% and 4.1% respectively. Additionally, there were other areas that were characterized in this classification such as Sand coverage and land region which constituted 6.3%. Area with no recognizable data (No data) was at 7.3%.

In 2020, There were notable changes observed as the image classifier could detect certain regions (Figure 25) with respect to coral reef classification and eliminated data which was irrelevant. Shallow water dominated the land classification covering 15.4km^2 that accounted for 63% of the area. Land region (Figure 26) was notably reduced to 0.41% (0.1km^2). The proportion of string coral bleaching had increased to 50% while medium bleaching decreased to 28.3% with light bleaching showing a short increase to 21%. Sand covered 1.6km^2 and regions that marked as no data accounted for 2.7km^2 at 1.9% and 7.4% respectively.

In 2024, the area of Deep water significantly expanded from 3.4km^2 (13.8%) to 11km^2 (29%). The land region increased from 0.4% to 5.3 % due to the image classification that showed more area as compared to 2020. Conversely, Sand areas decreased from 2.8km^2 to 0.48km^2 (11.48% - 1.25%) either indicating a change in the coral reef structure or the addition of artificial construction areas such as resorts or walls (to prevent soil erosion and flooding).

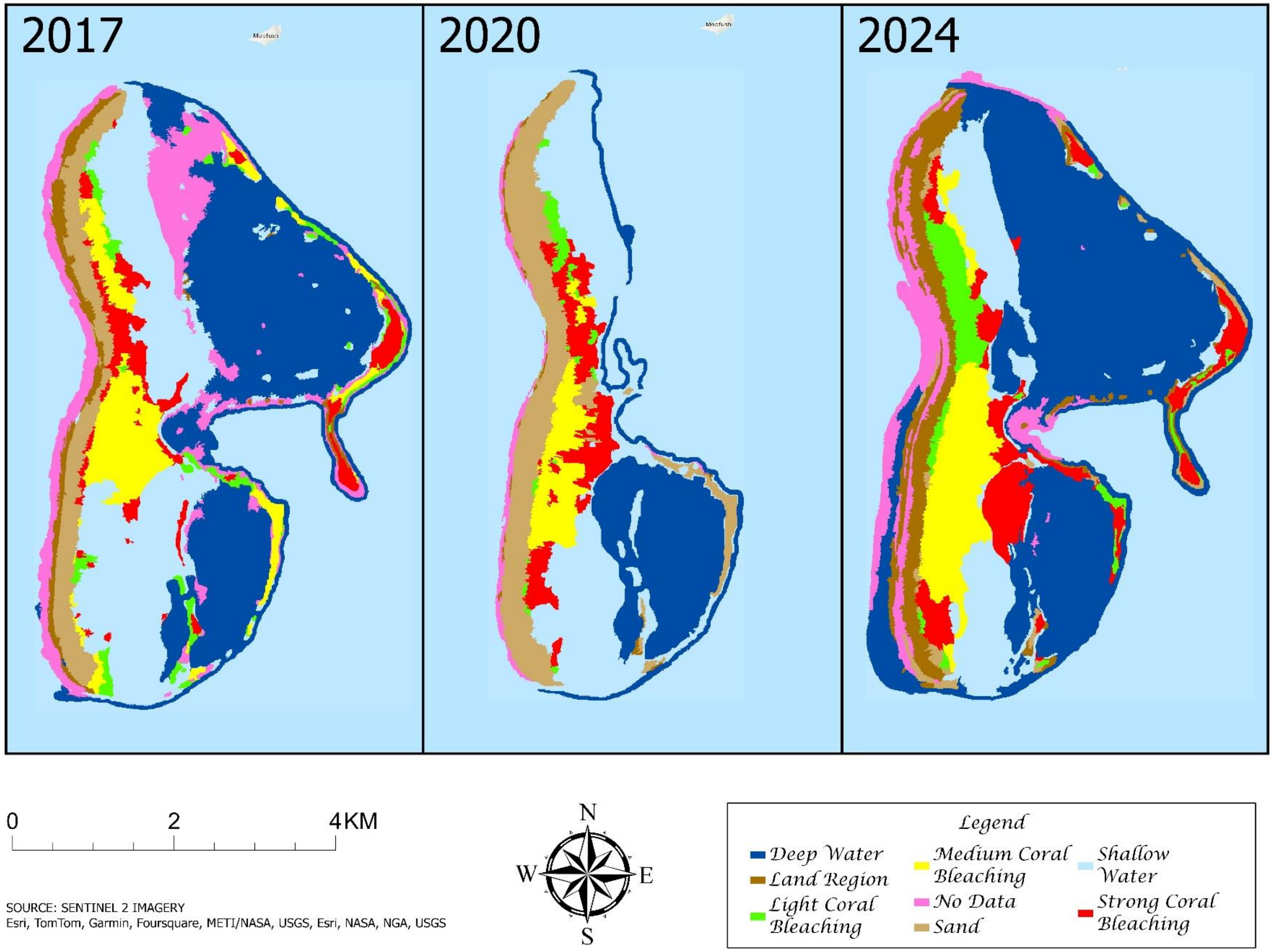


Figure 24 - Land Classification of Island 1 from 2017 to 2024

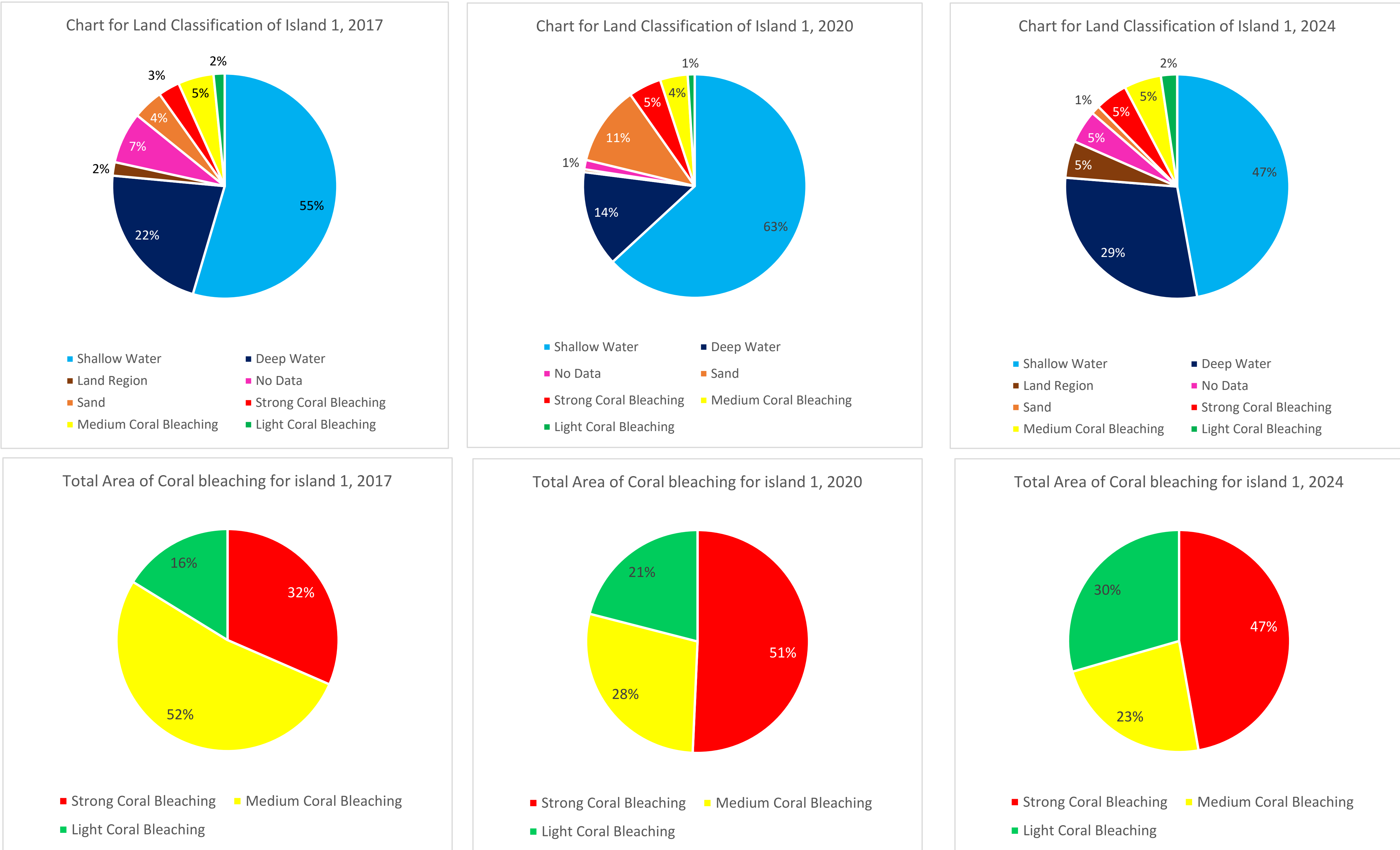


Figure 25 - Land classification and distribution of coral bleaching for island 1 from 2017 to 2024

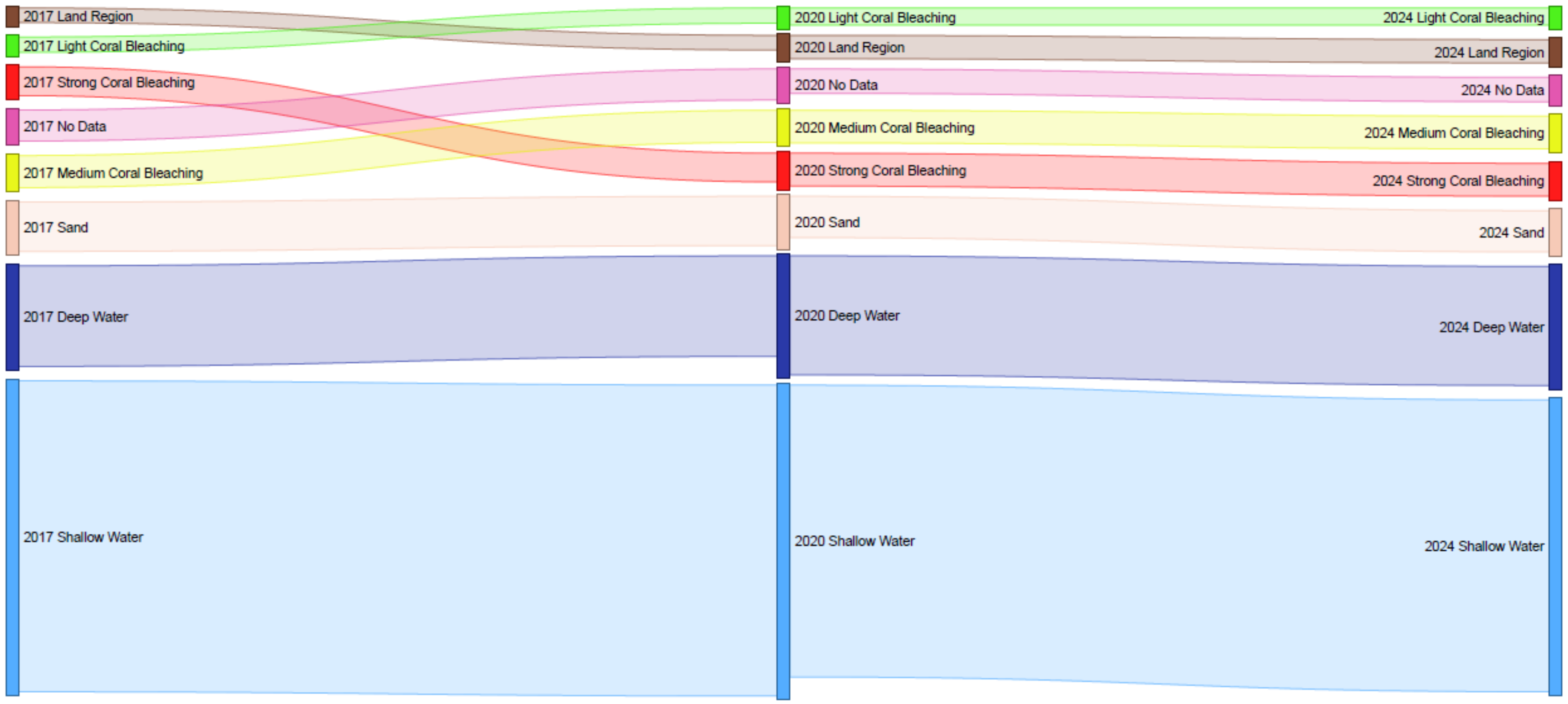


Figure 26 – Sankey Graph showing the transition of land classification from 2017 to 2024 for island 1

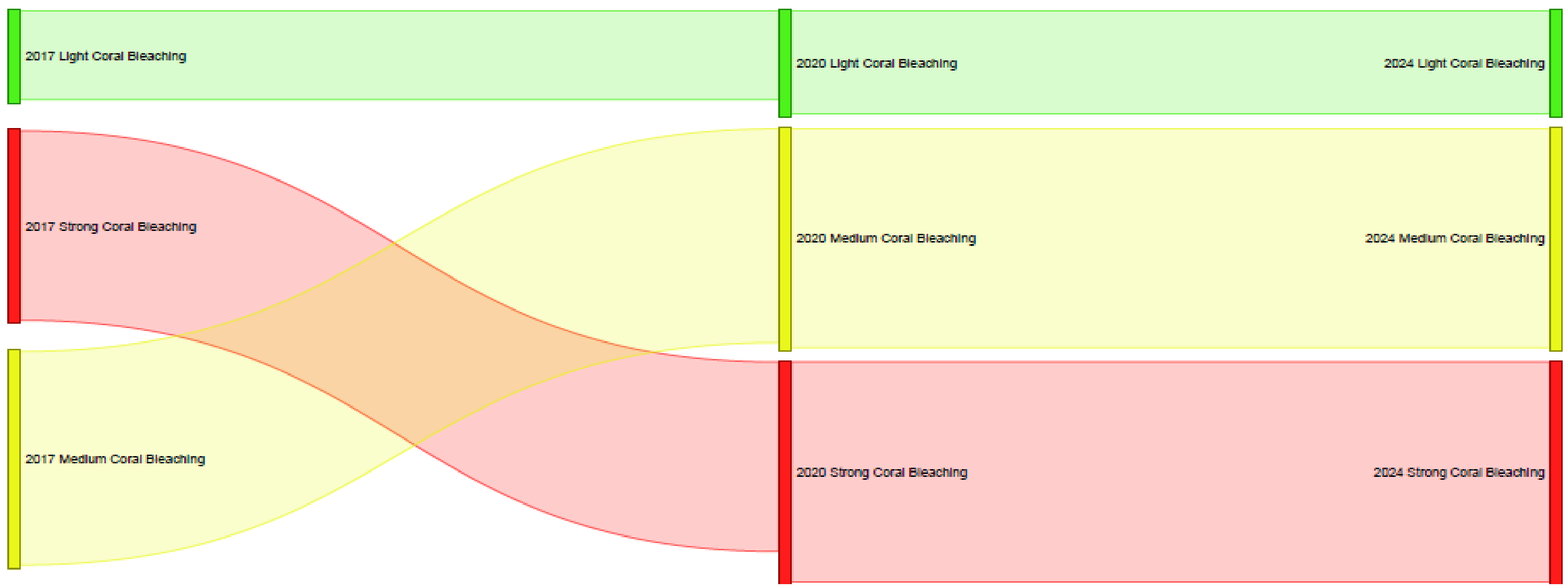


Figure 27 -Sankey Graph showing the Coral bleaching Distribution of Island 1 from 2017 to 2024

5.1.2 Trend Study for Bleached areas

As a comparison to other islands, from Figure 29, Island 1 shows decreased chlorophyll levels from 2017 to 2020 and a partial recovery in 2024, indicating that there are mixed trends of bleaching across the island. Light bleaching showed a decrease in area from 2017 to 2020 and then considerably increase in 2024 from 0.24 km^2 to 0.9 km^2 respectively. A significant increase in bleaching areas across all the categories suggests that island 1 has a very sensitive coral reef system.

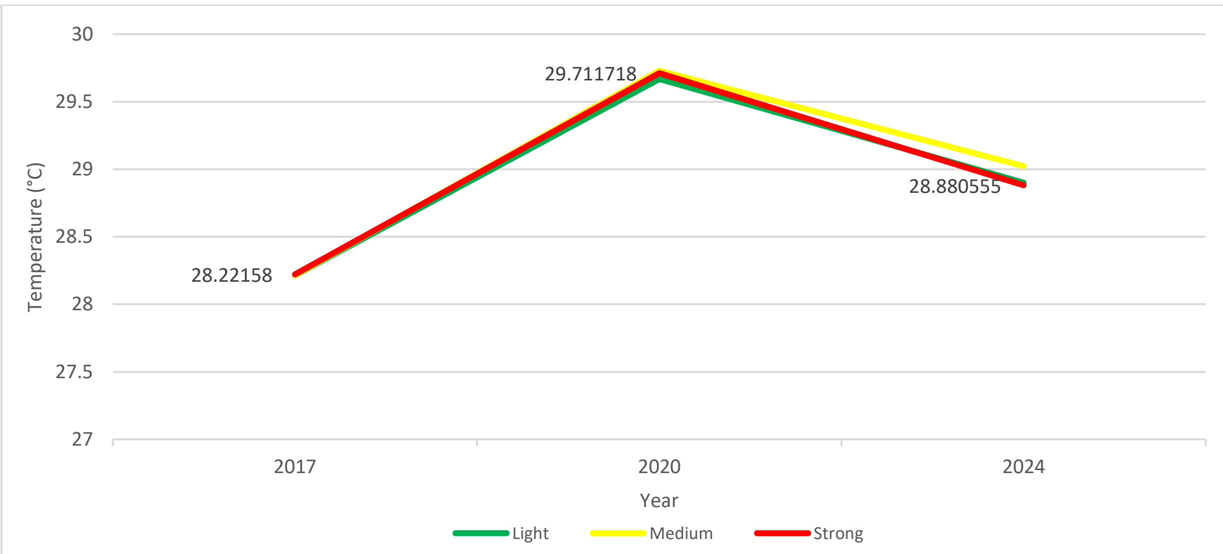


Figure 28 - Mean Temperature (°C) Trend for Island 1 by coral bleaching categories

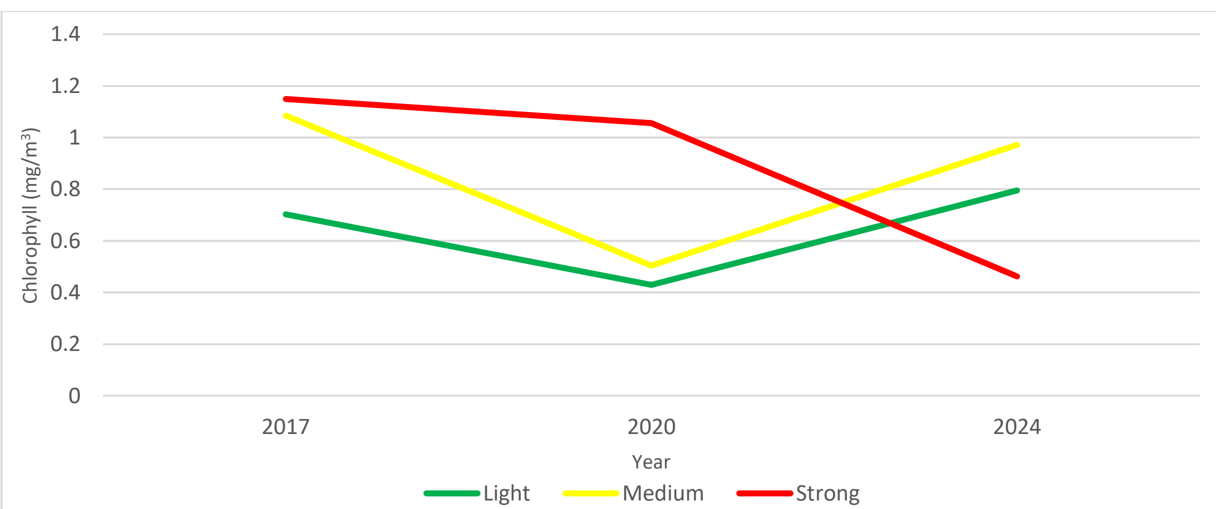


Figure 29 - Mean Chlorophyll (mg/m^3) Trend for Island 1 by coral bleaching categories

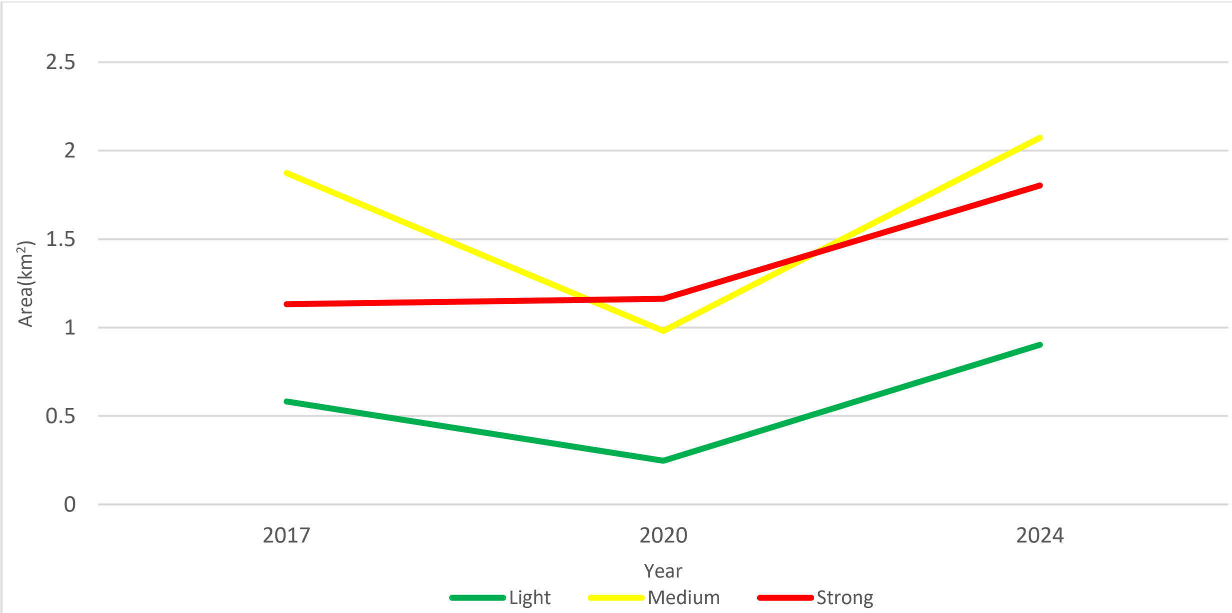


Figure 30 - Mean Area (km^2) Trend for Island 1 by coral bleaching categories

An observation in the conversion of bleaching patterns

The conversion patterns i.e. light to medium and medium to strong coral bleaching are severely influenced by sustained high temperatures and chlorophyll patterns causing a stress on the coral environment.

From figure 30, we can ascertain a decrease from 2017 to 2020 which could indicate a resilience to the effects of bleaching on the coral environment due to the limited interaction between anthropogenic structures and the reduced occurrence in tourism during 2020, because of the covid 19 pandemic observed in light coral bleaching. However, by 2024, the increased chlorophyll levels with a definite increase (difference from light to medium bleaching) from 0.42mg/m^3 in 2020 to 0.18 mg/m^3 and constant high temperatures could have intensified the effects of coral bleaching showing a conversion to medium coral bleaching.

5.1.3 Correlation Matrix of bleached areas

Using this method, we can identify the relation between 2 variables and understand how they influence each other and the impact they have on other elements from figure 31.

Correlation between Mean temperature and chlorophyll

There is a negative correlation between temperature and chlorophyll levels (-0.45) which could mean that the temperature and chlorophyll values tend to decrease indicating that high temperatures could have a negative impact on chlorophyll levels in the water affecting the coral ecosystem.

Correlation between Mean chlorophyll and bleached area

A moderate positive correlation of 0.42 is observed between the chlorophyll levels and the bleached area. This would mean that higher chlorophyll levels are identified or attached with larger areas with coral bleaching indicating conditions that promote the growth of chlorophyll could be caused by the higher nutrient demand in the region.

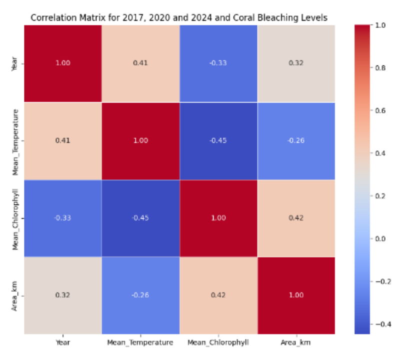


Figure 31 - Correlation Matrix of Island 1

Correlation between Mean temperature and bleached area

A weak negative correlation is observed between temperature and the bleached area (-0.26). This would imply that an increase in temperature could be associated with a decrease in the coral bleaching area. Due to the relatively weak correlation, other factors could also play a significant role in the determination of bleaching affecting the area.

5.2 ISLAND 2

5.2.1 Land Classification

In 2017, island 2 was characterized by the same classes indicated in island 1. Shallow water comprised 12.5% (0.6 km^2) of the total area and deep water comprised 27.2% (1.4km^2). Observing Figure 32, we can notice that the land region was significantly smaller, covering just 0.02km^2 (0.38%). Strong coral bleaching covered 0.04km^2 representing 0.7% of the total area. Medium coral reefs were the most dominant in the bleaching category, covering 0.5km^2 that accounted for 9.65% of the island. Finally, light coral bleaching covered 0.29km^2, with 5.3% of the total area. Sand regions occupied 0.6km^2 (12%) of the total area. No data indicating that there was no quantifiable information available, covering 12% of the area noted in figure 34.

By 2020, there were significant changes observed over island 2. Shallow water regions decreased to 0.67km^2 representing 13.2% of the total area. A reduction in deep water regions at 1.04 km^2 (20.7%). Sand regions slightly increased to 0.7 km^2 (13.8%). Strong coral bleaching areas (figure 35) significantly increased to 0.16 km^2 covering 3.2% of the total area. The medium coral bleaching also saw a similar change covering 0.63 km^2 that accounted for 12.5% of the island's area. On the other hand, the light coral bleaching regions decreased to 0.13 km^2 at 2.7% of the total area. This shows that the coral reefs have drastically been bleached over a three-year interval. The ratio of No data decreased to 29% due to improved data accuracy with a shift in the land region being classified.

In 2024, the land classification changed even more, shallow water areas increased to almost 18% whereas deep water regions increased to 2km^2 accounting for 37% of the area. The land region was reduced to 0.04 km^2 representing just 0.74%. Sand areas saw a substantial decrease to 0.008 km^2 accounting for 0.15% of the total area. The area covered by strong coral bleaching increased to 0.53km^2 representing 9.72%. The Medium coral reefs covered 1.3km^2, accounting for 25% of the island's area indicating a substantial growth whereas the light coral reefs saw a change covering 0.3km^2 at 5.7% of the total area.

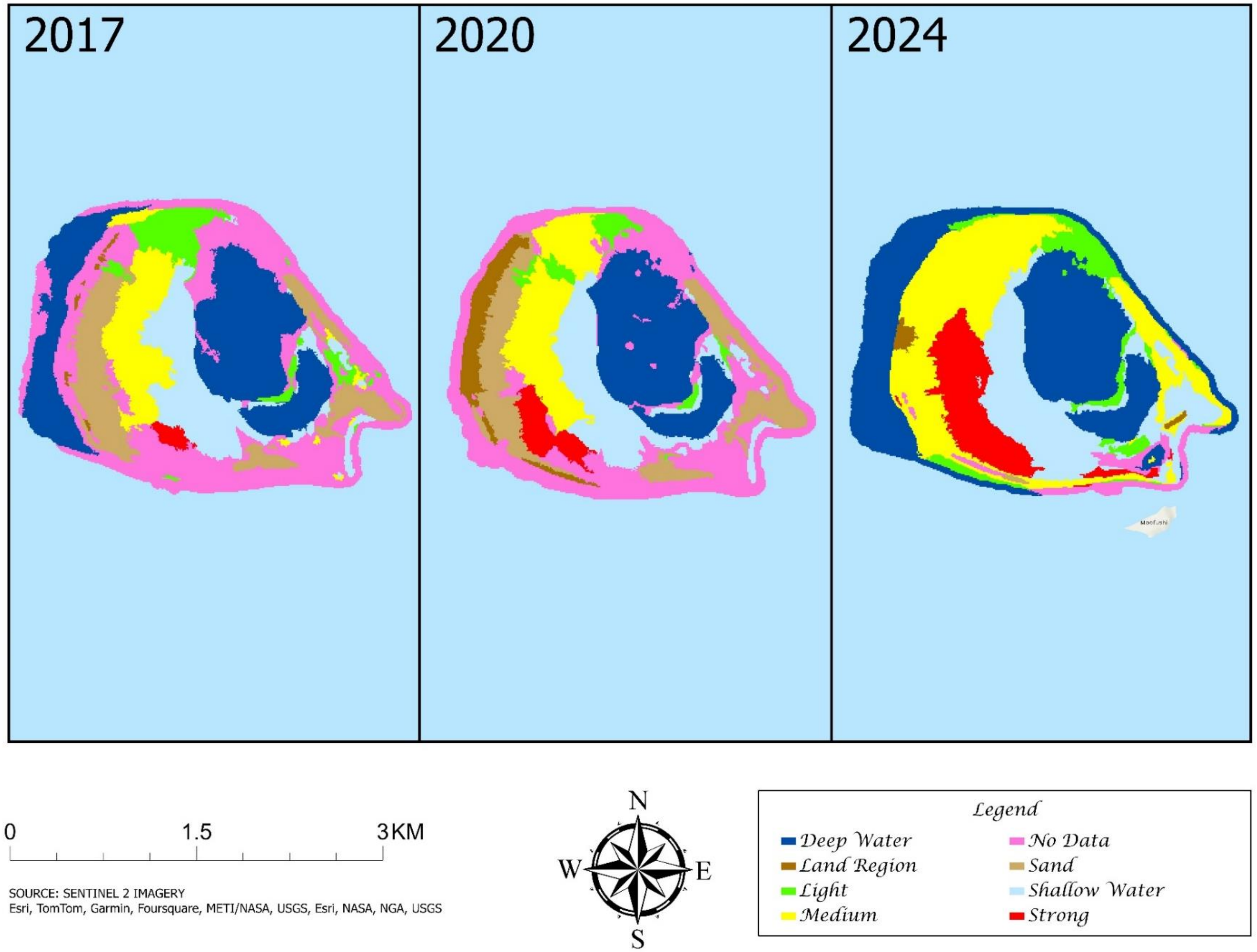


Figure 32 - Land Classification of Island 2 from 2017 to 2024

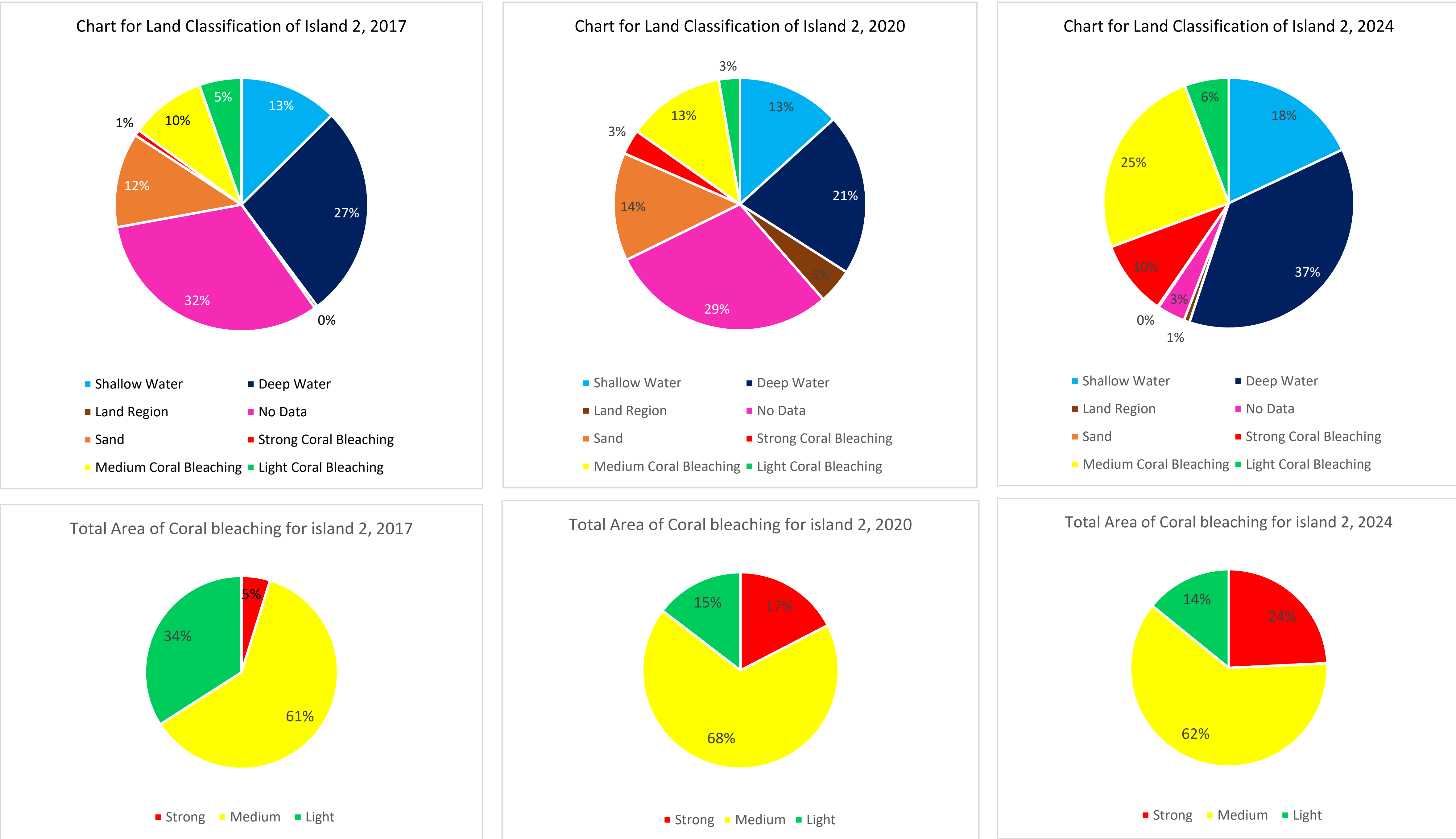


Figure 33 - Land classification and distribution of coral bleaching for island 2 from 2017 to 2024

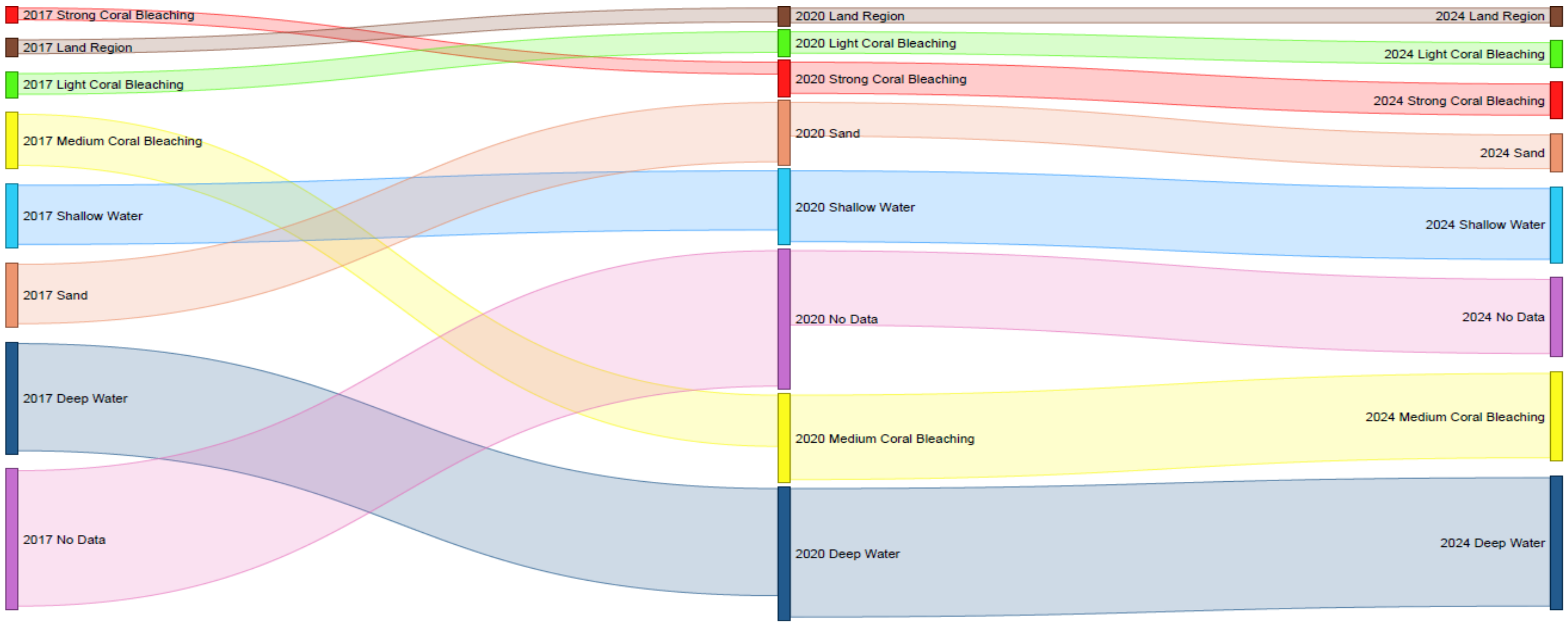


Figure 34 - Sankey Graph showing the transition of land classification from 2017 to 2024 for island 2

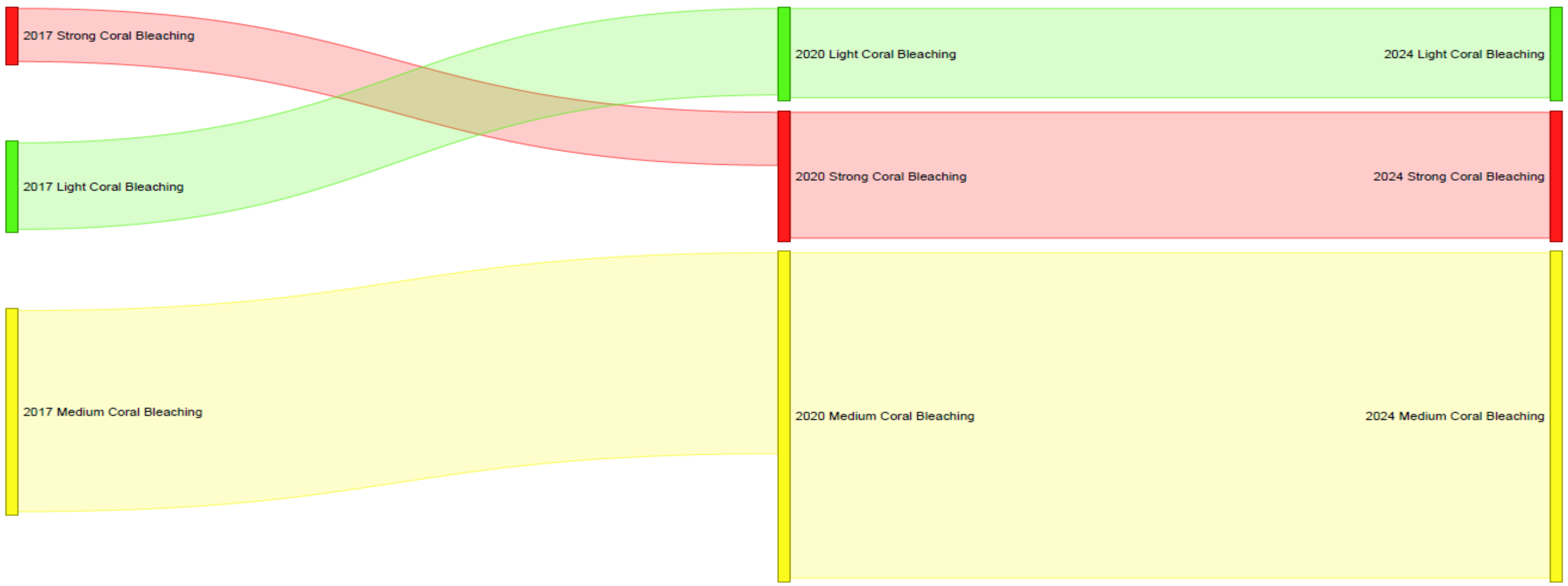


Figure 35 - Sankey Graph showing the Coral bleaching Distribution of Island 2 from 2017 to 2024

5.2.2 Trend Study for Bleached areas

There is a significant decrease in chlorophyll trends observed in figure 37 in all the areas as compared to island 1 (figure 30) which shows a mixed trend with general variation in the data. General warming and decrease in chlorophyll levels across all bleaching categories indicate a reduction in nutrient availability leading to the loss of the planktonic community which in turn causes stress to the coral ecosystem. The decrease in light bleaching areas (0.29 km^2 to 0.13km^2) from 2017 to 2020, have shifted to medium bleached areas from 0.53 km^2 to 0.63 km^2 respectively and a small difference observed in strong bleaching from 0.04km^2 to 0.16km^2 shows a smaller progression of bleaching as compared to island 1. We can conclude that light and strong bleaching areas have increased significantly, although strong bleaching regions remained stable attributing to the island's perimeter.

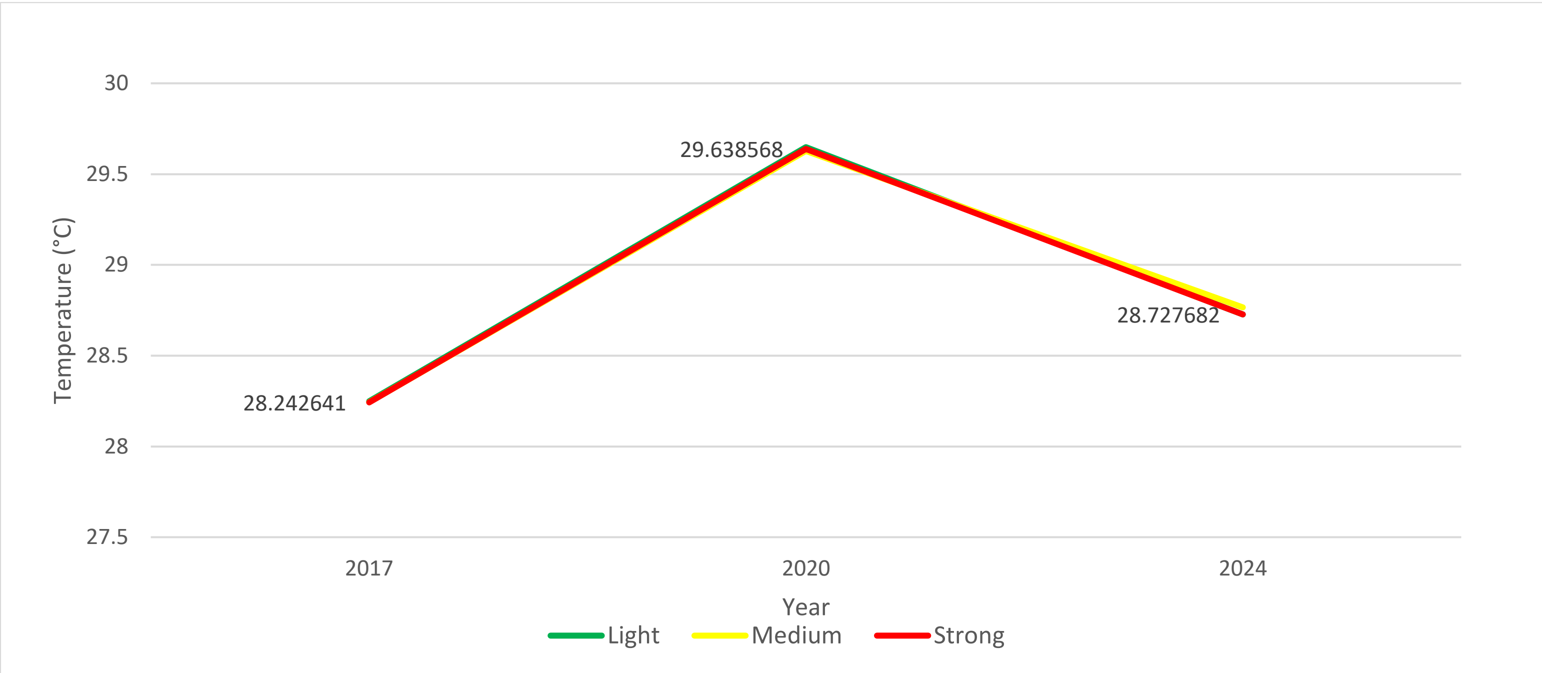


Figure 36 - Mean Temperature (°C) Trend for Island 2 by coral bleaching categories

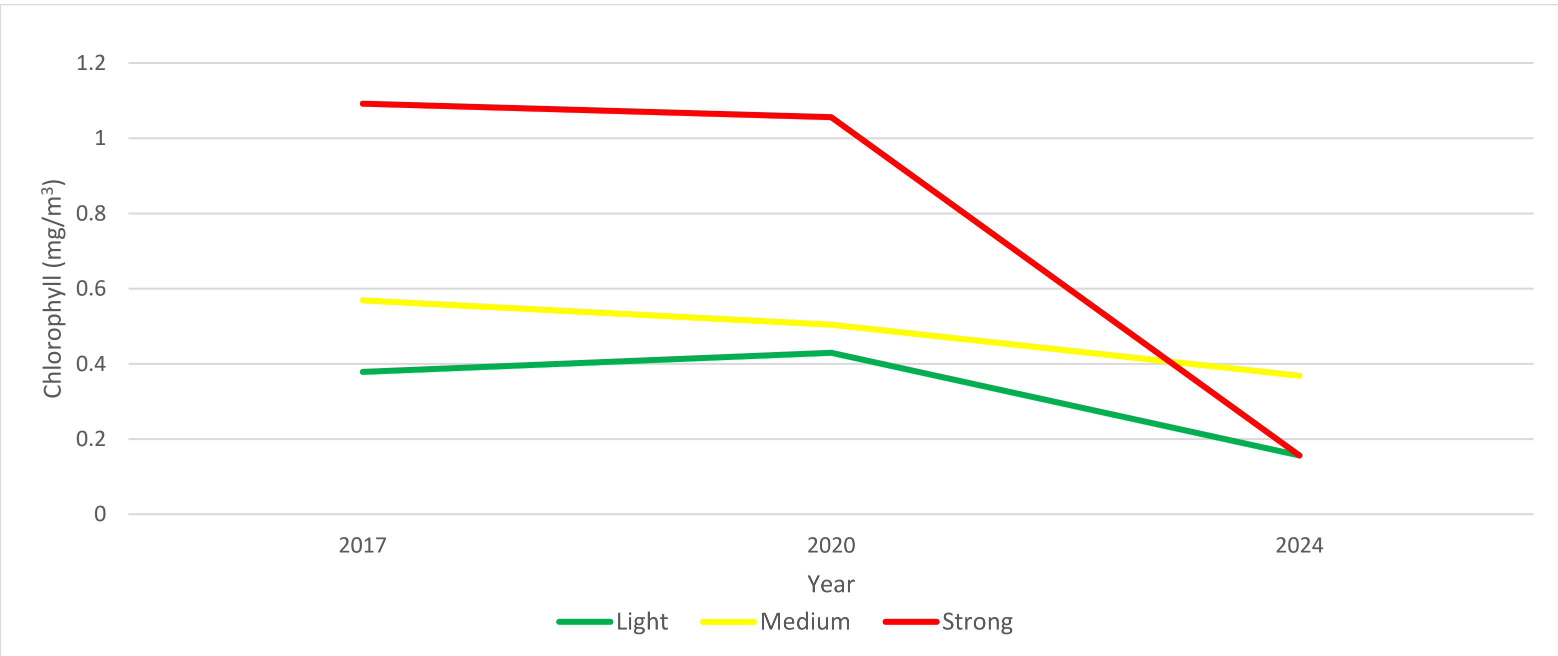


Figure 37 - Mean Chlorophyll (mg/m^3) Trend for Island 2 by coral bleaching categories

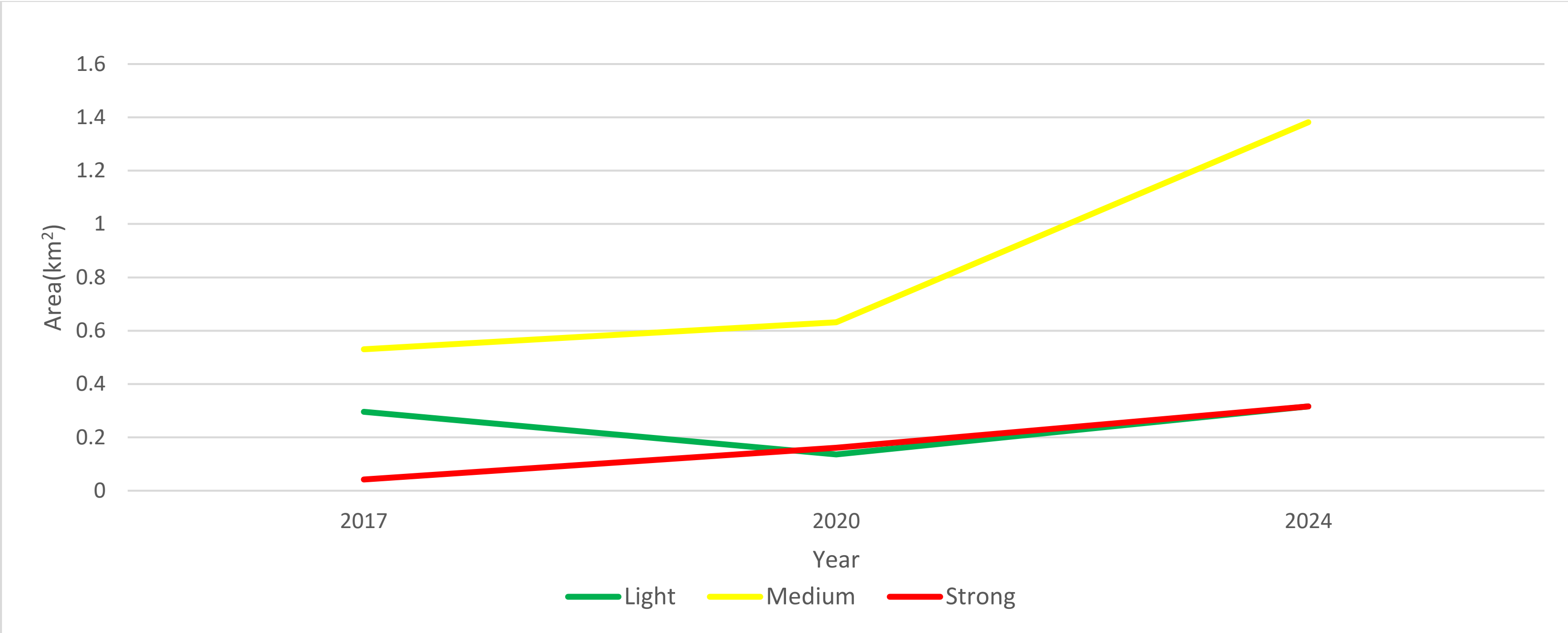


Figure 38 - Mean Area (km^2) Trend for Island 2 by coral bleaching categories

5.2.3 Correlation Matrix of bleached areas

Correlation between Mean temperature and chlorophyll

There is a weak positive correlation of 0.05, that almost shows no relationship between temperature and chlorophyll levels

Correlation between Mean temperature and bleached area

A very weak correlation of -0.06 tells us that there is no linear link between the temperature and coral bleached areas.

Correlation between Mean chlorophyll and bleached area

A negative correlation of -0.42 indicates that higher chlorophyll levels are associated with smaller areas that are affected by coral bleaching.

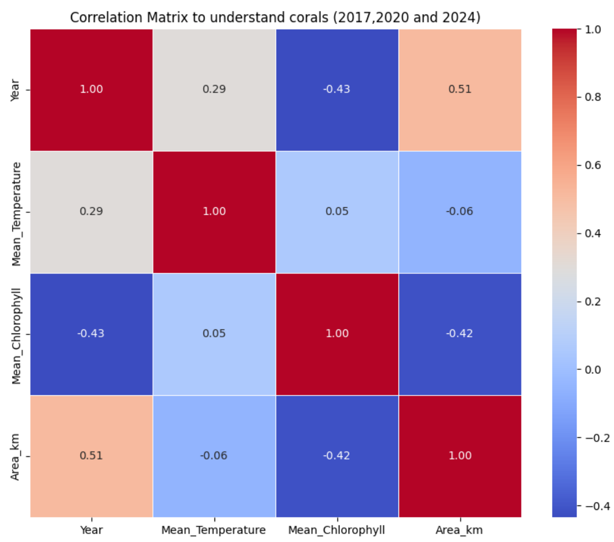


Figure 39 - Correlation Matrix of Island 2

Figure 39 explains the correlation with passage of time, shows a temperature rise and decrease in chlorophyll levels affected by coral bleaching. This would imply that the coral health conditions are worsening with extensive bleaching events occurring as the years progress.

5.3 ISLAND 3

5.3.1 Land Classification

From figure 40, we notice that Shallow water covered around 0.9 km^2, accounting for 9.3% of the total area in 2017. Deep water engulfed 46% with 4.4 km^2. However, Sand occupied 1.3km^2 or 13% of the area while the amount of information not available in the not data category was summarized to 4.5%. The coral region covered 9.7km^2, that accounted to 6% of the total area as seen in figure 41. This region was divided based on strong coral beaching that covered 0.3km^2 (3.3%), medium coral bleaching at 0.15km^2 (1.5%) and light coral bleaching at 0.12km^2 (1.2%).

By 2020, there were significant changes observed over the land region. Figure 41 shows Shallow water represented 10.9% of the total area that expanded to 0.8km^2. There was almost no change in the deep-water class as it saw a reduction to 3.8km^2 to 42.7% of the total area indicating that more area was accessible as seen in figure 42. The sand region remained normal at 1.3km^2 covering over 14% of the area. Coral reefs occupy 8.9km^2 (6.6%) of the total area with strong coral bleaching decreasing to 1.8% rounded over 0.16km^2, whereas Medium and Light coral bleaching increased to 2.6% and 2.1% at 0.2km^2 and 0.18km^2 respectively. The No data category decreased considerably to 1.3% indicating that more information was present and could be identified in the classifier.

In 2024, shallow water covered 1.4km^2 accounting for 15% of the total area. The most dominant category was still the deep-water area with 3.3km^2 or 34%. Sand covered 1.4km^2 representing 15% of the area. The strong bleaching category significantly increased to 0.4km^2 at 5% of the total area with medium bleaching at 3% and light bleaching at 2.2%. The total area covered by coral reefs was 9.7km^2 which occupied 10% of the total area.

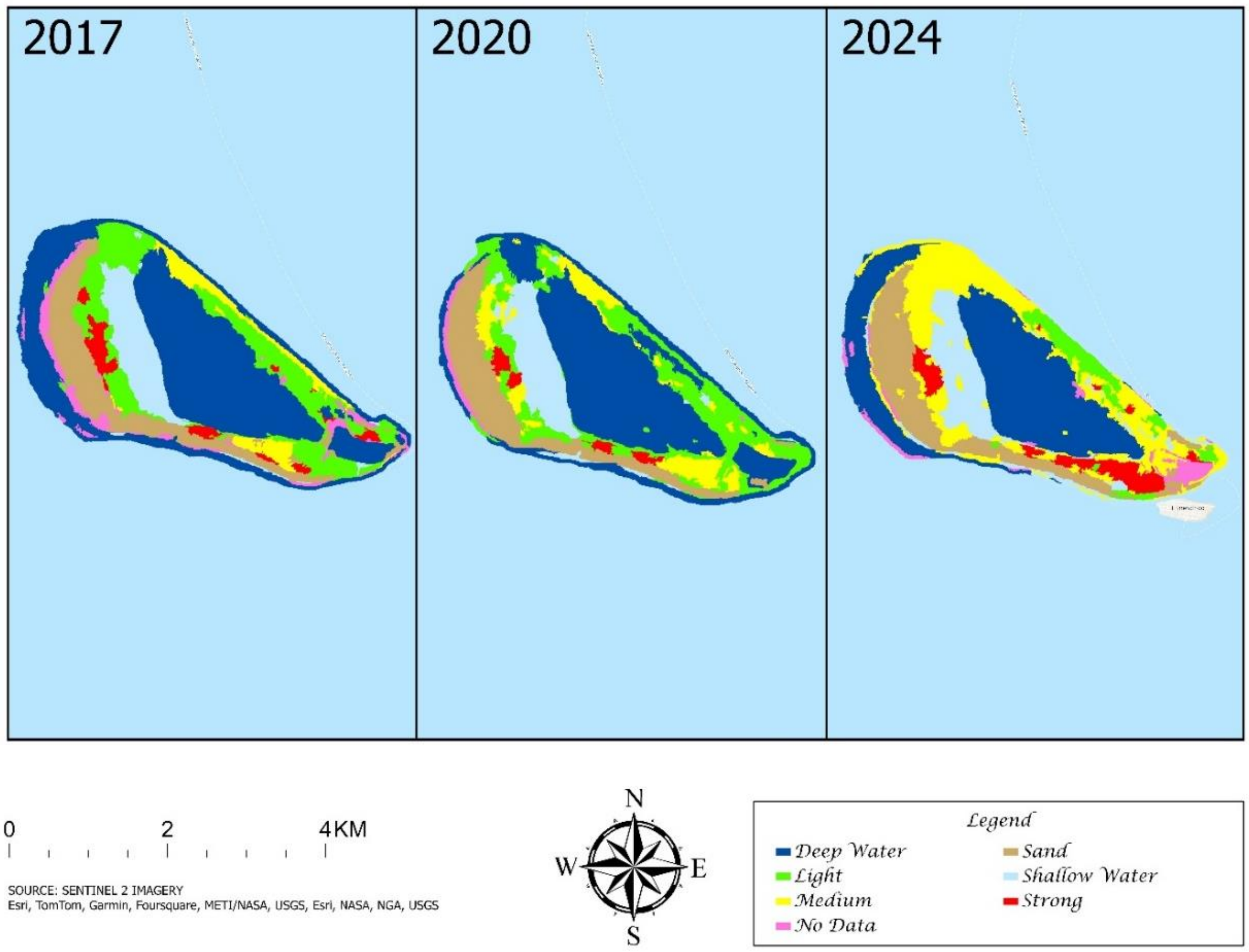


Figure 40 - Land Classification of Island 3 from 2017 to 2024

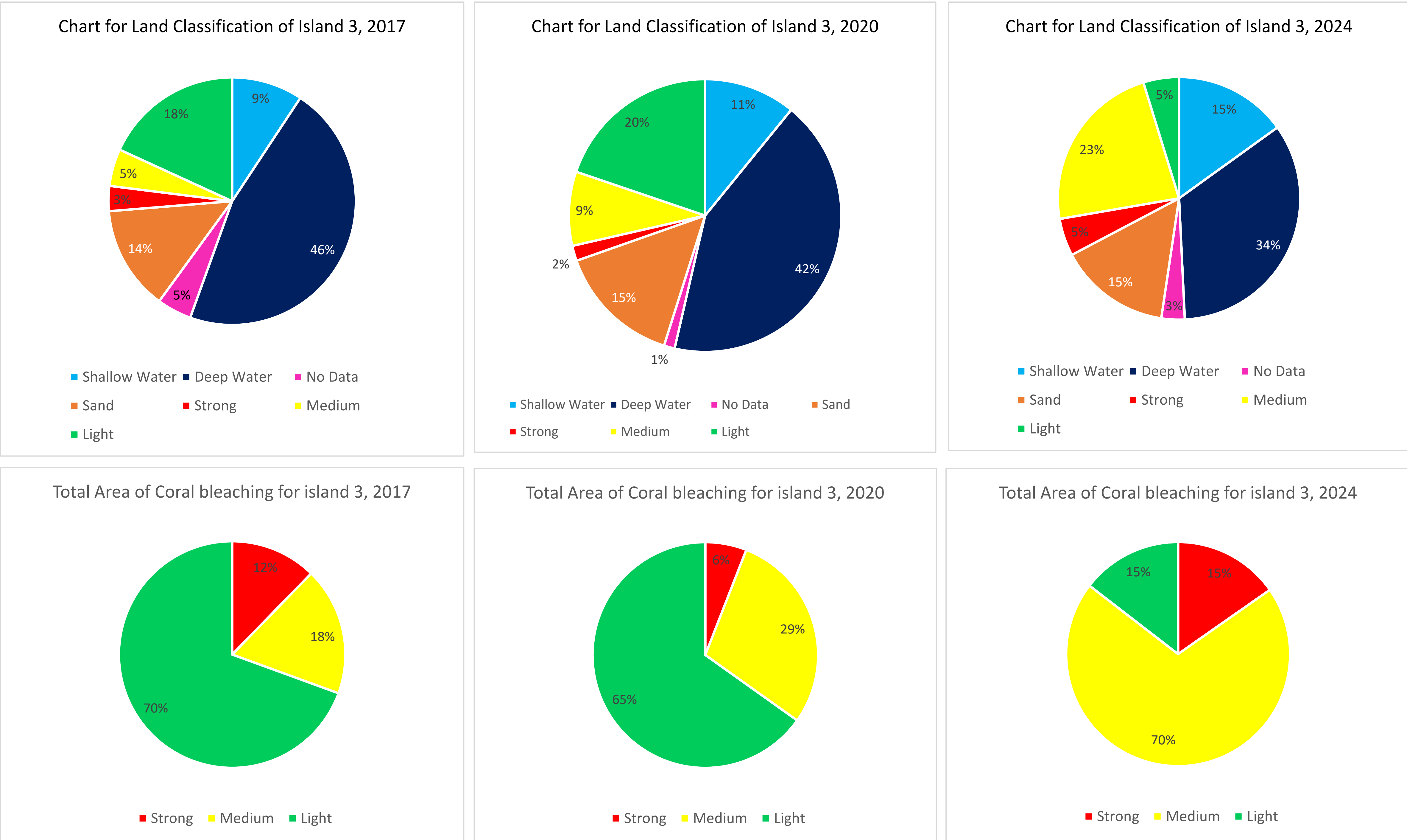


Figure 41 - Land classification and distribution of coral bleaching for island 3 from 2017 to 2024

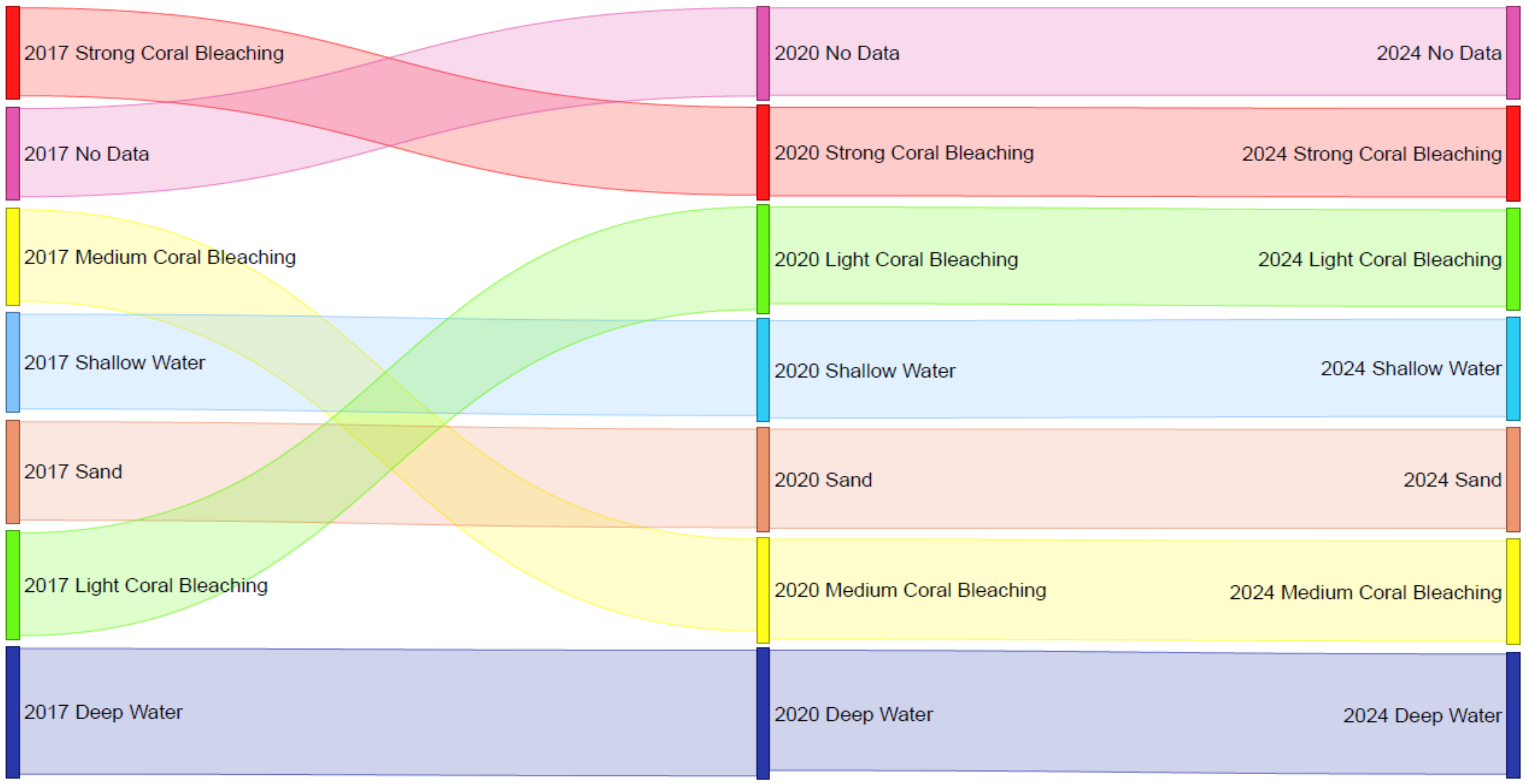


Figure 42 - Sankey Graph showing the transition of land classification from 2017 to 2024 for island 3

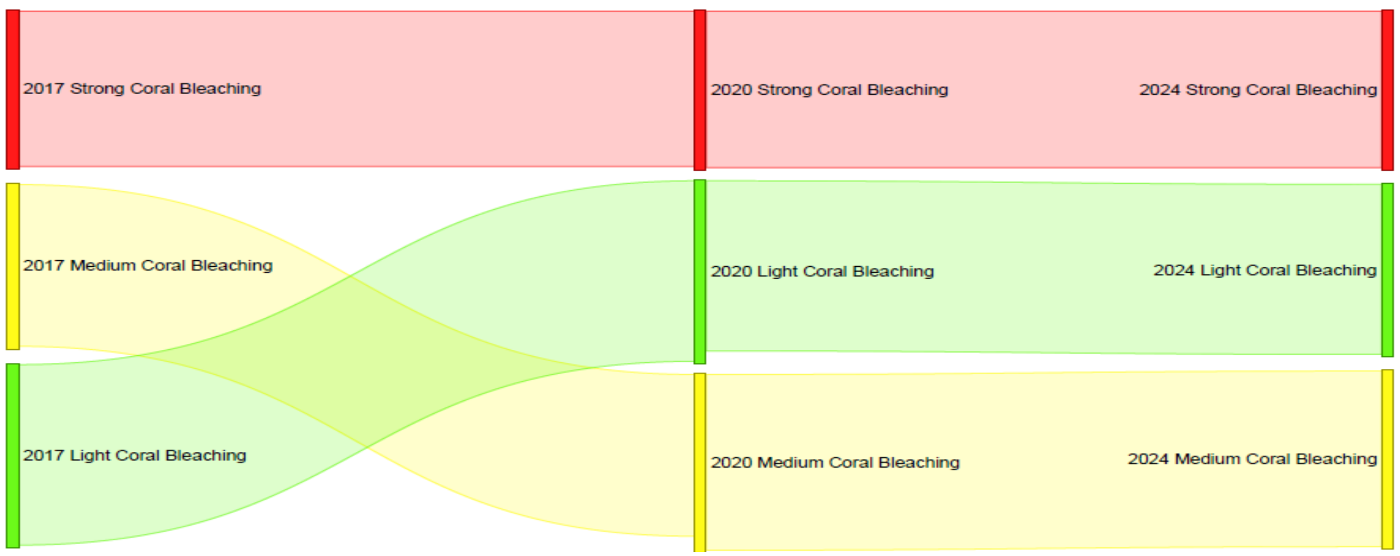


Figure 43 - Sankey Graph showing the Coral bleaching Distribution of Island 3 from 2017 to 2024

5.3.2 Trend Study for Bleached areas

In Figure 45, chlorophyll levels in light bleaching regions displayed a significant increase by 2024, from 0.59mg/m^3 rising from 0.03mg/m^3 at a difference of -0.56mg/m^3. This is almost an absolute variance from island 1 (0.09 mg/m^3) and island 2 (-0.22 mg/m^3). As with all the islands, the temperature showed a constant pattern of rising temperatures from 2017 to 2020 and then a gradual decrease observed in 2024 which could indicate a regional warming phenomenon.

The bleaching data from 2020 to 2024 showed a predictable decrease in light bleaching (-1.31km^2) and a very remarkable increase in medium bleaching (+1.45km^2). This change could suggest that many light bleaching areas from 2024 transformed to medium bleaching regions. Consequently, Island 3 showed a small change in strong bleaching patterns over the same time frame (+0.32km^2).

From this data, we can ascertain that island 3 is witnessing a generalized increase in medium bleaching, tending towards strong bleaching levels. This trend could become much worse in the future if environmental protection measures are not implemented by the community or the local government of the Maldives.

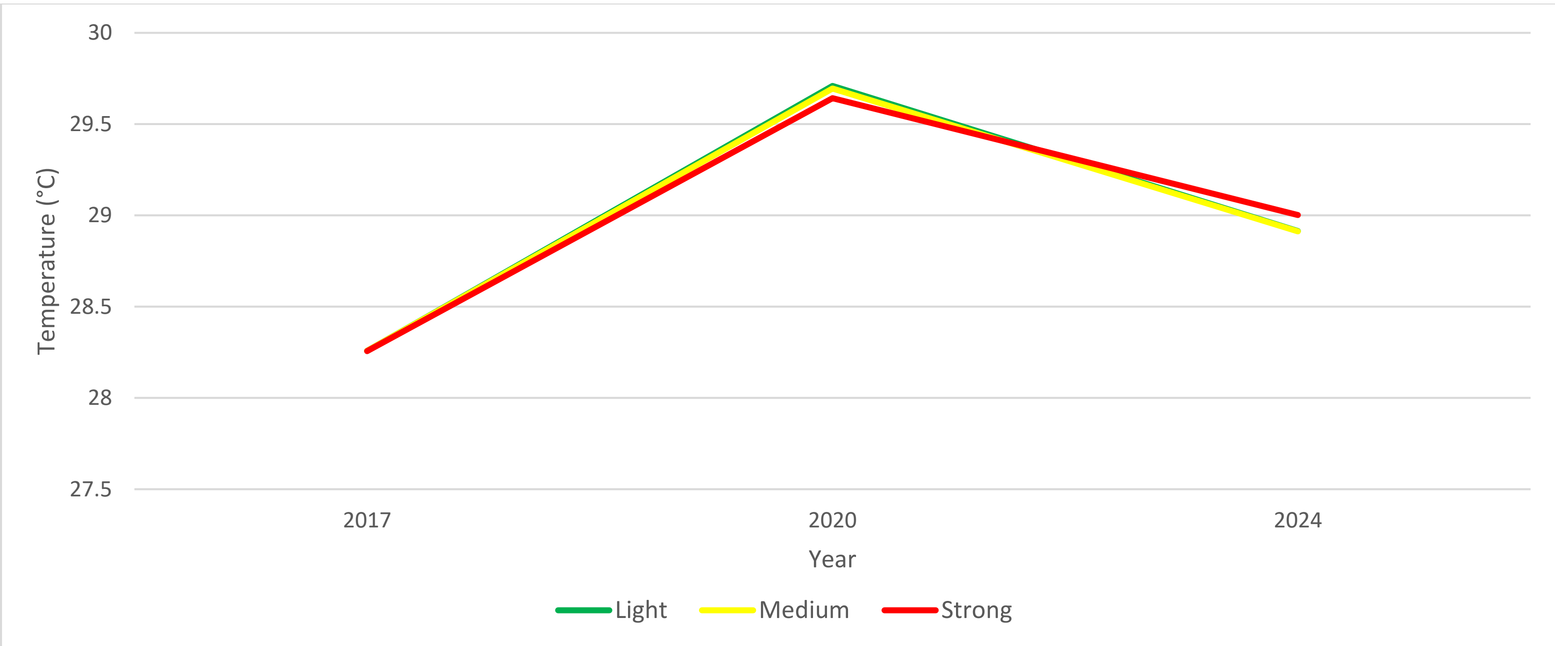


Figure 44 - Mean Temperature (°C) Trend for Island 3 by coral bleaching categories

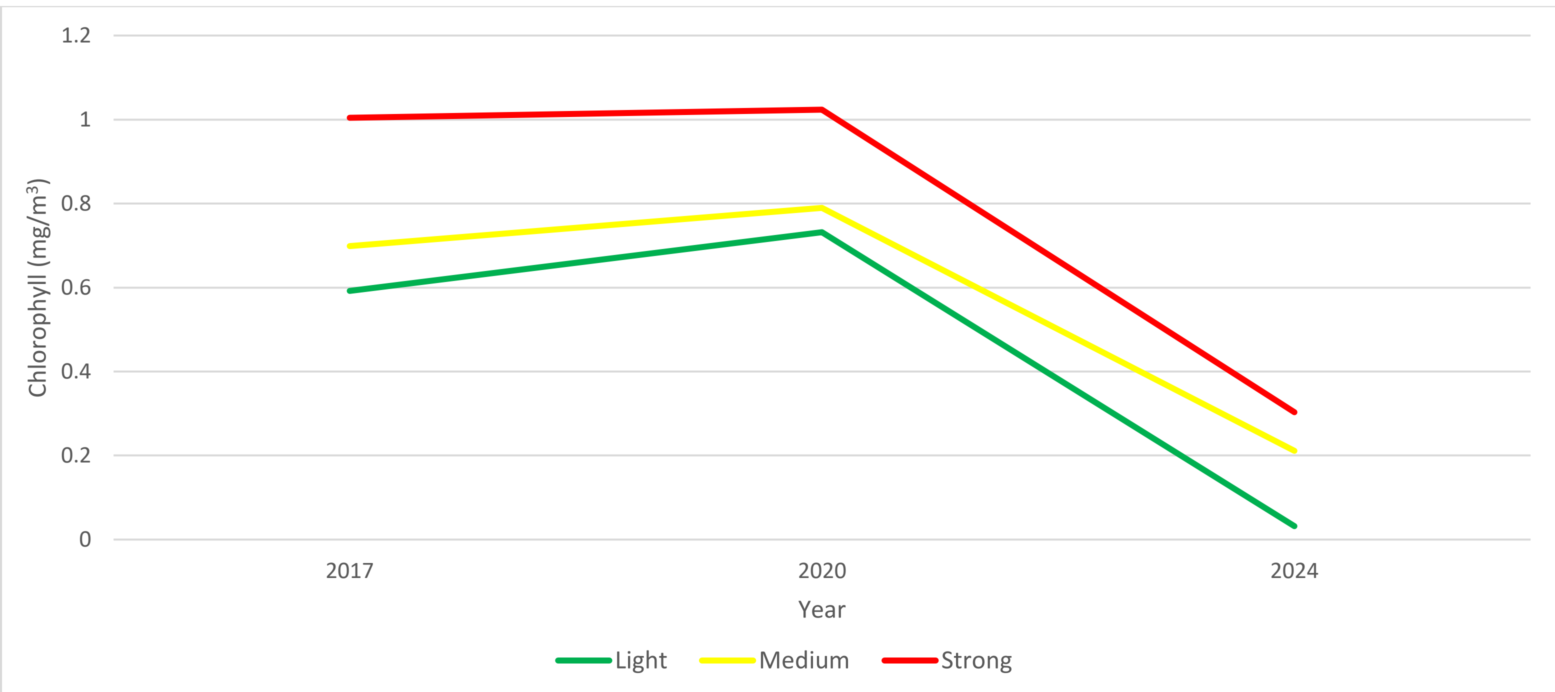


Figure 45 - Mean Chlorophyll (mg/m^3) Trend for Island 3 by coral bleaching categories

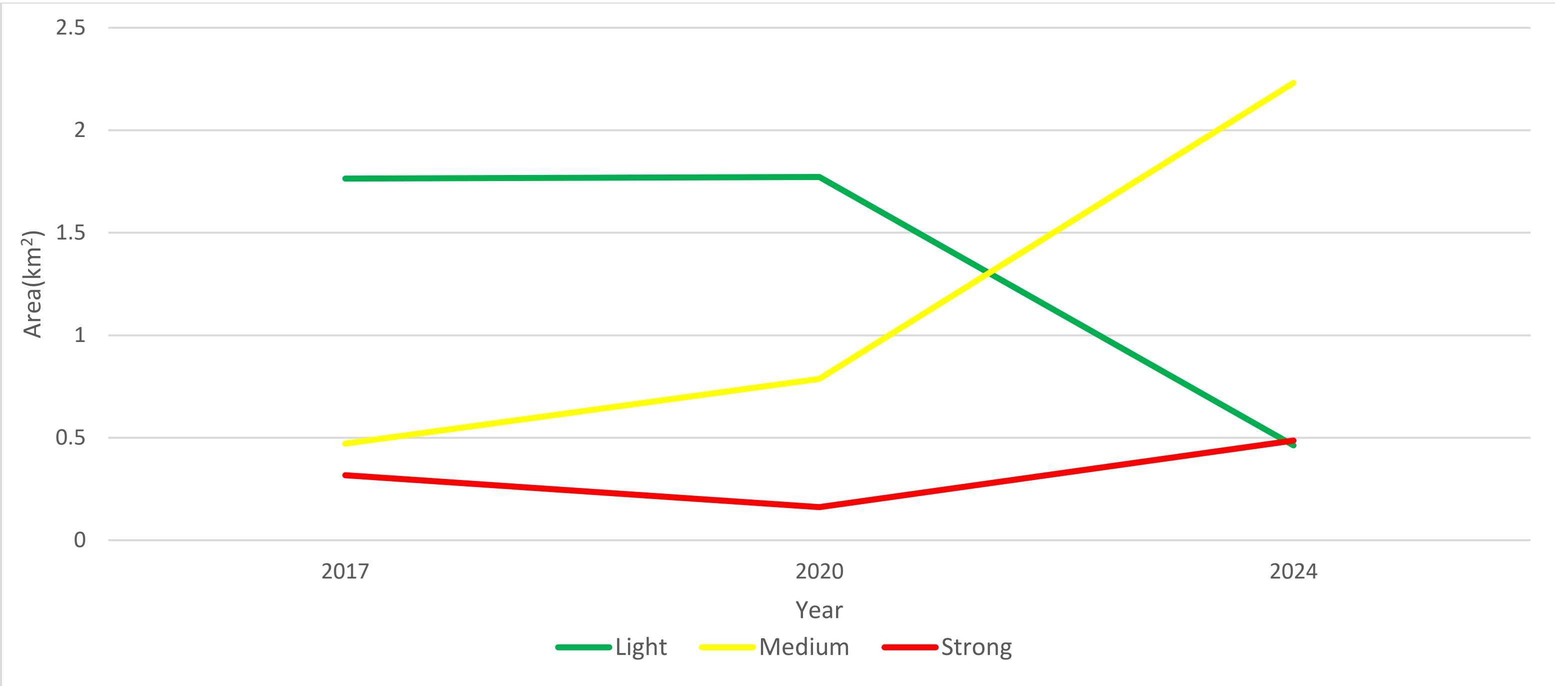


Figure 46 - Mean Area (km²) Trend for Island 3 by coral bleaching categories

5.3.3 Correlation Matrix of bleached areas

Correlation of Mean Temperature with Mean Chlorophyll

There is a weak positive correlation of 0.12 with almost no observable relationship between temperature and chlorophyll levels.

Correlation of Mean Temperature with Bleached Areas

Similar to mean chlorophyll, there is a very weak positive correlation with the bleached area of 0.03, indicating that the temperature has no effect on the selected bleached areas.

Correlation of Mean Chlorophyll with Bleached Areas.

A weak negative correlation of -0.3 is observed, implying that higher chlorophyll levels are often associated with smaller areas that are impacted by coral bleaching.

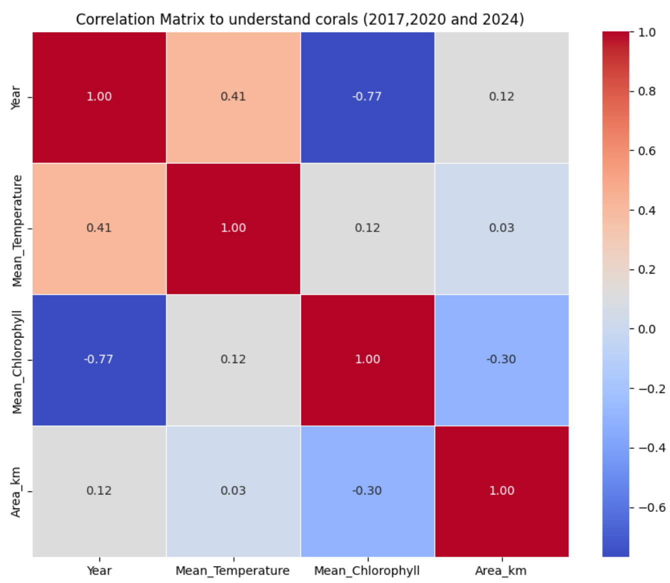


Figure 47 - Correlation Matrix of Island 3

These correlations indicate that with the passage of years, changes in both temperature and chlorophyll levels over the area affected bleaching even more. In the case of island 3, chlorophyll levels were extremely crucial to the coral ecosystem as compared to temperature variations.

5.4 ISLAND 4

5.4.1 Land Classification

In 2017, shallow water covered around 1.6 km^2, that constituted 29% of the total area. Deep water areas however constituted just 3.8% of the total area which was about 0.2km^2. Sand covered the second largest category spanning over 1km^2 covering 19.4%. The coral ecosystem comprised a total area of 1.8km^2 which accounted for 33% of the total area. Strong bleaching levels occupied 0.18km^2 that represented 3% of the total area. On the other hand, medium bleaching was observed over an area of 0.5km^2 accounting for 9.3% and the most dominant category was light bleaching that covered 1.1km^2 crossing 20% of the total area. Areas with no Data accounted for 14%.

By 2020, island 3 had changed, which was noticeable in the land classification categories. Shallow water was still the largest category but had reduced to 1.5km^2 covering 27% of the area. Due to the decrease in the No data category to 8%, other categories such as Sand increased significantly to 1.3km^2 constituting 23% of the total area. Deep water regions increased to 0.6km^2 at 11%. The total coral reef cover decreased to 1.5km^2 representing 28% of the total area. Light bleaching areas decreased to 0.7km^2 accounting for 12% of the total area, whereas Medium bleaching areas increased to 0.78km^2 covering 14% of the area. Strong bleaching reduced significantly to 0.1 km^2 representing 1.7km^2.

In 2024, shallow water increased by 2km^2 that was 36% of the total area. Deep water regions also expanded to 0.8km^2 accounting for 16% of the total area. Sand areas decreased to 1km^2 covering 11.3%. The coral reef coverage declined even further to 1.4km^2 constituting 23% of the total area. Light bleaching areas decreased to 0.41km^2 covering 6% of the total area like medium bleached areas that decreased to 0.2km^2 representing 4%. There was a notable increase in strong bleaching areas as it expanded to 0.7km^2, constituting 12% of the total area.

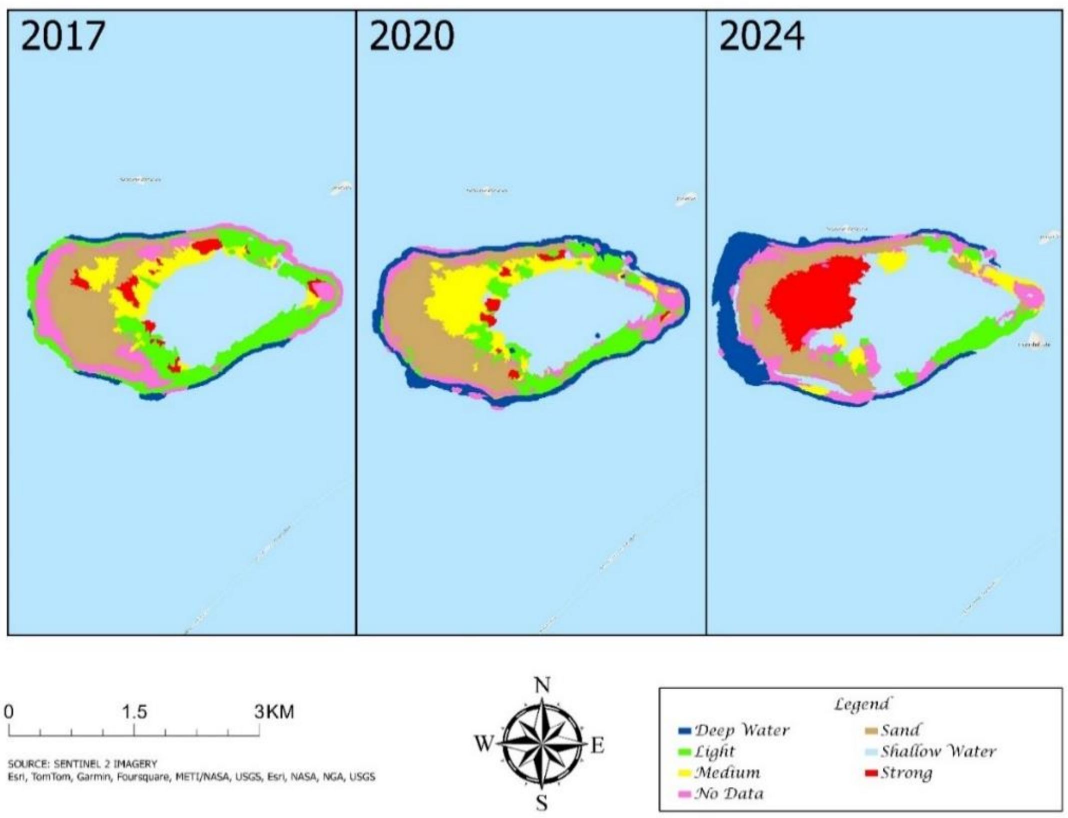


Figure 48 - Land Classification of Island 4 from 2017 to 2024

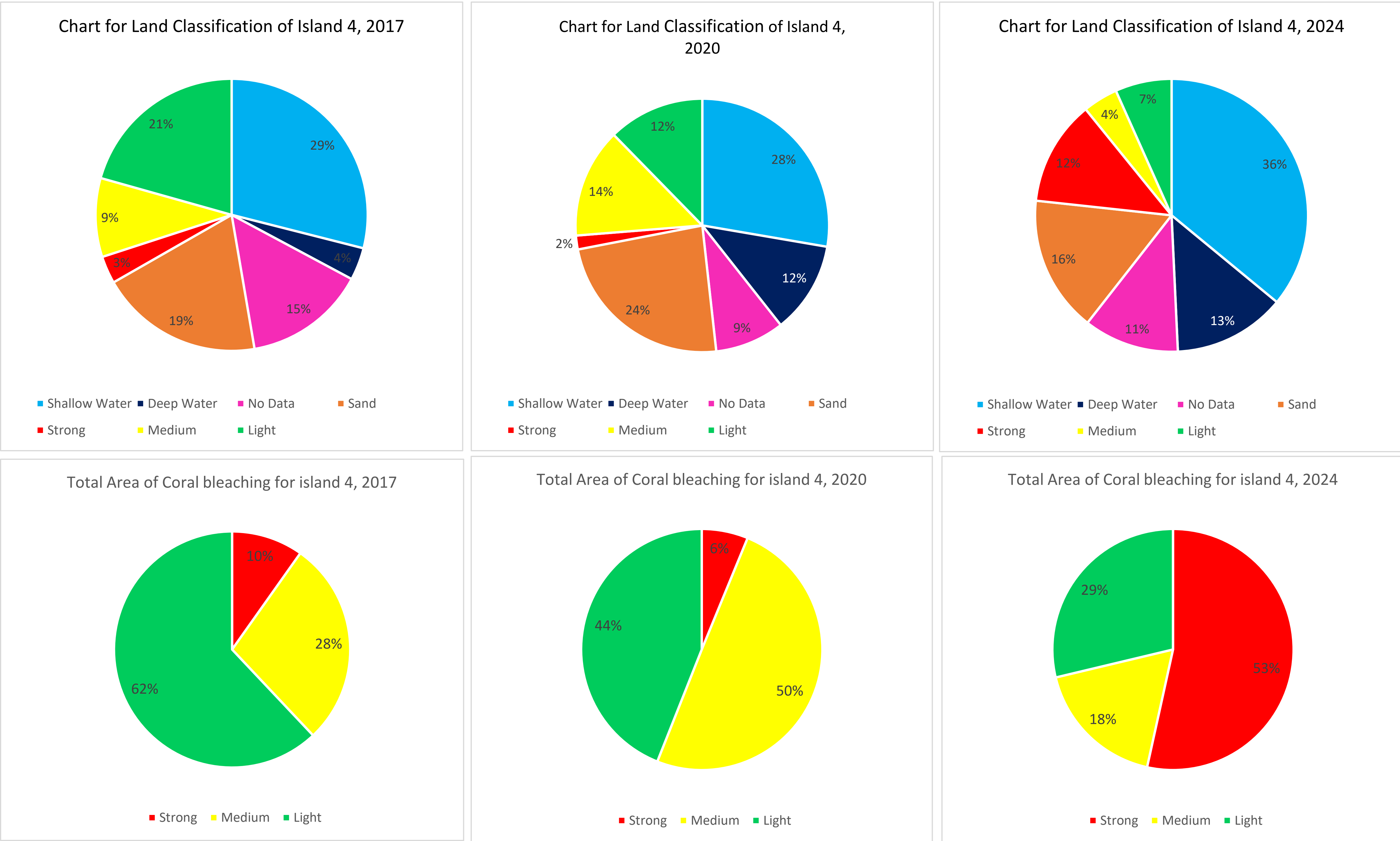


Figure 49 - Land classification and distribution of coral bleaching for island 4 from 2017 to 2024

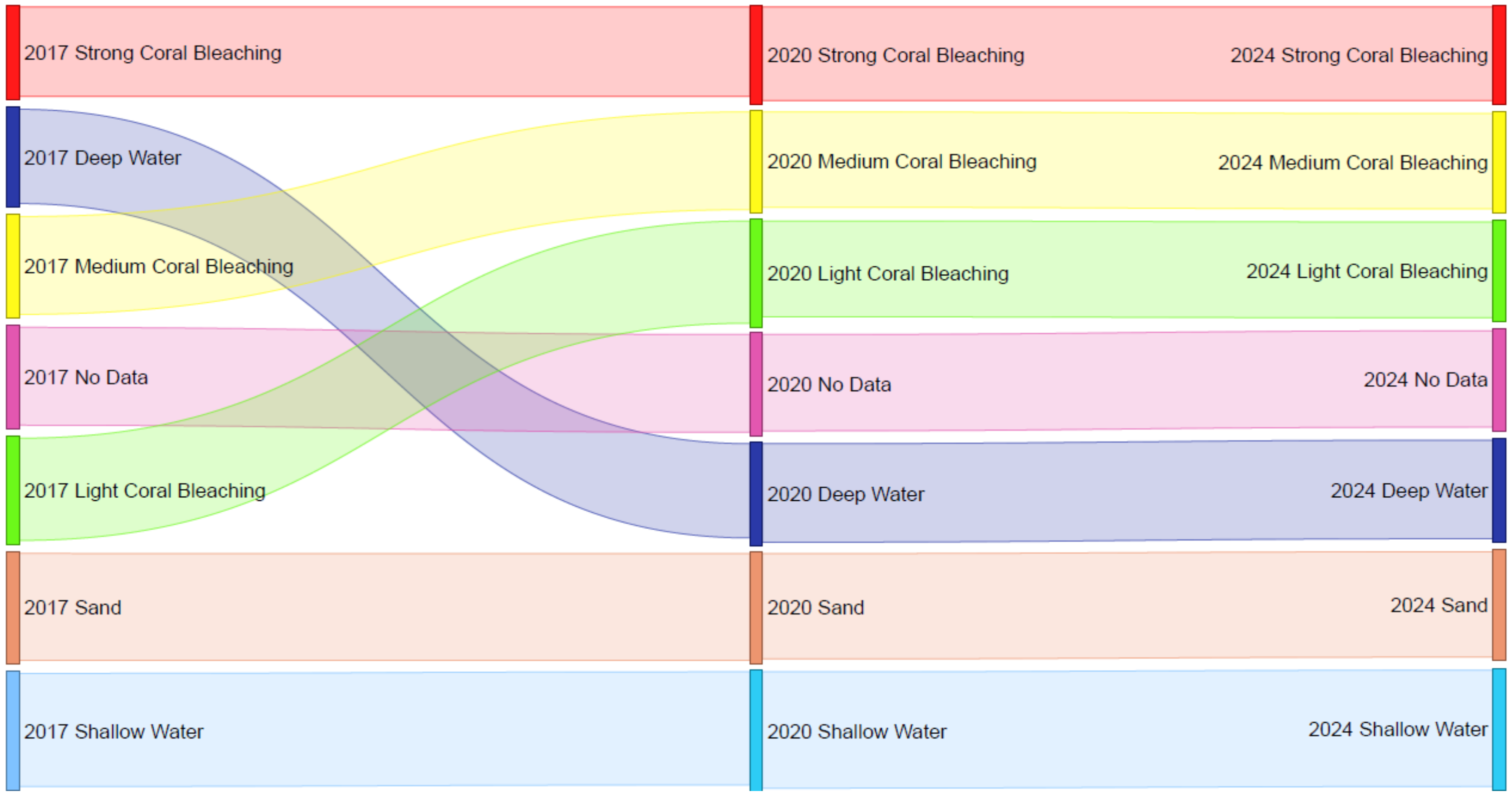


Figure 50 - Sankey Graph showing the transition of land classification from 2017 to 2024 for island 4

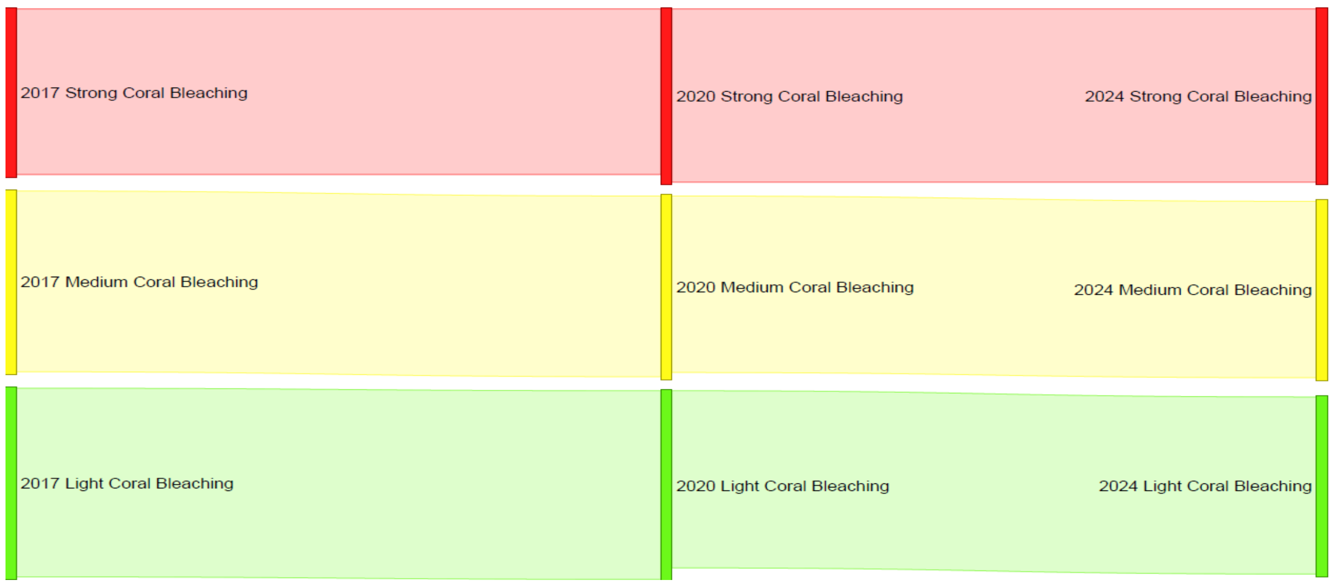


Figure 51 - Sankey Graph showing the Coral bleaching Distribution of Island 4 from 2017 to 2024

5.4.2 Trend Study for Bleached areas

The coral ecosystem of this island saw high levels of stress from 2017 to 2024 and a peak at around 2020 due to high temperature levels and variation in chlorophyll patterns across all the categories. The change in chlorophyll levels saw an initial increase in 2017 (0.46 mg/m^3) to 2020 (0.60 mg/m^3) and then decreased by 2024 (0.24 mg/m^3) in light bleaching areas. Medium bleaching areas followed a similar trend rising from 0.82 mg/m^3 in 2017 to 0.91mg/m^3 in 2020, dropping to 0.24 mg/m^3. Strong bleaching regions in fact showed relatively stable levels from 0.86 mg/m^3 in 2017 to 0.80 mg/m3 in 2020 and then rising to 0.57 mg/m^3. The data shows transitions of light bleaching areas transformed to medium bleaching areas from 2017 to 2020 at 0.45 km^2. A small change was observed from 2020 to 2024 as these trends reversed to a minimum value indicating a small hope for probable bleaching recovery as these coral reefs adapt to an ever-changing environment. The drastic spike in bleaching levels indicates that the corals found on this island are highly sensitive to changes in the environment and immediate action needs to be taken to conserve them.

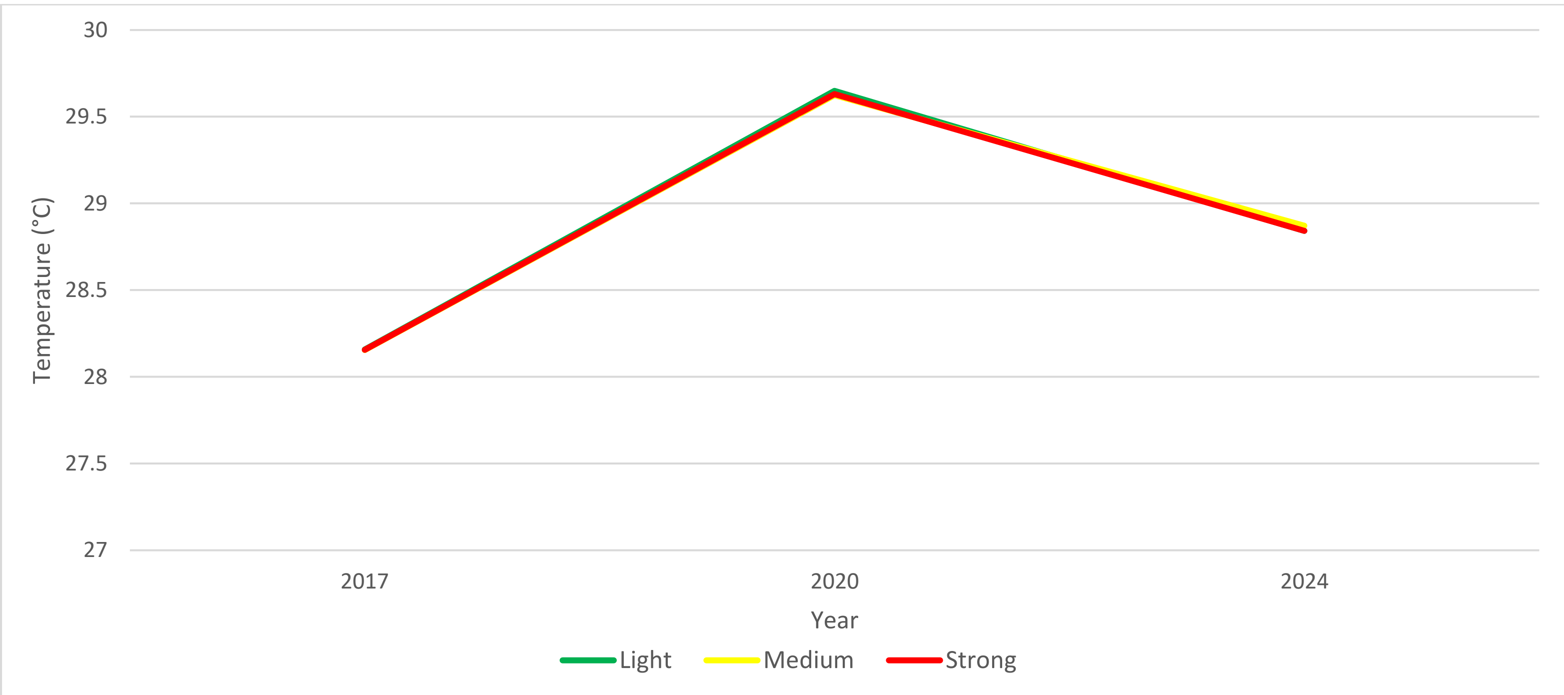


Figure 52 - Mean Temperature (°C) Trend for Island 4 by coral bleaching categories

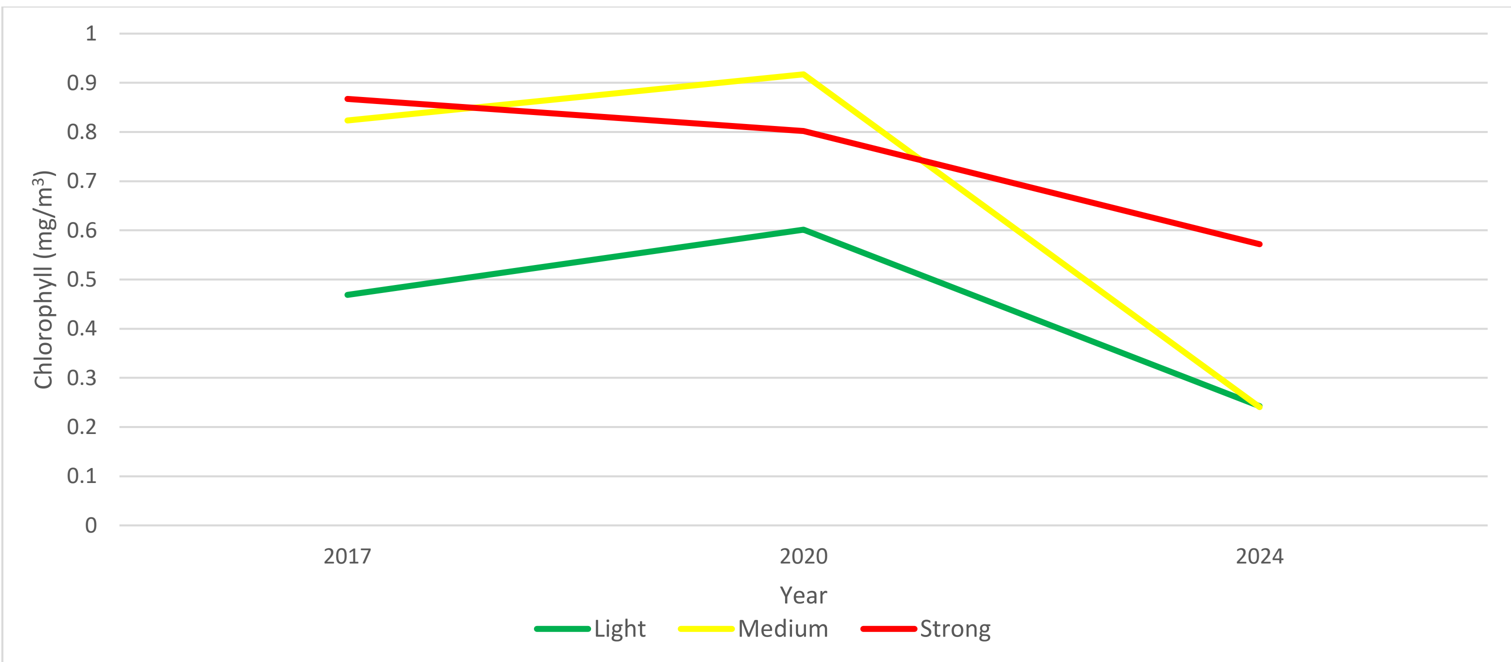


Figure 53 - Mean Chlorophyll (mg/m^3) Trend for Island 4 by coral bleaching categories

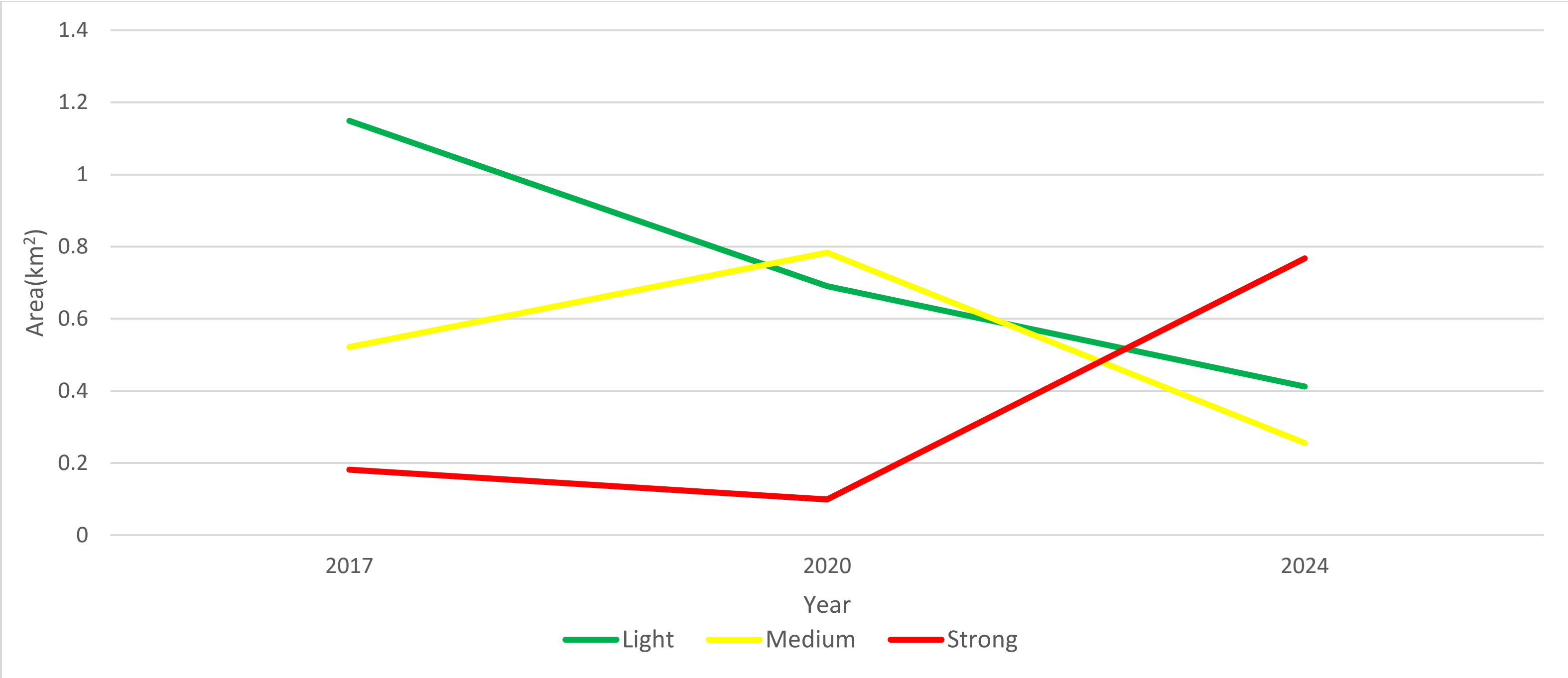


Figure 54 - Mean Area (km²) Trend for Island 4 by coral bleaching categories

5.4.3 Correlation Matrix of bleached areas

Correlation of Mean Temperature with Mean Chlorophyll

A weak positive correlation of 0.11 is observed with no relationship between temperature and chlorophyll levels.

Correlation of Mean Temperature with Bleached Areas

There is a very weak negative correlation of -0.12 indicating no relationship with temperature variations and the total area affected by coral bleaching.

Correlation of Mean Chlorophyll with Bleached Areas.

A weak negative correlation of -0.07 indicates no linear relationship between chlorophyll levels and the area affected by coral bleaching, related to the temperature variations.

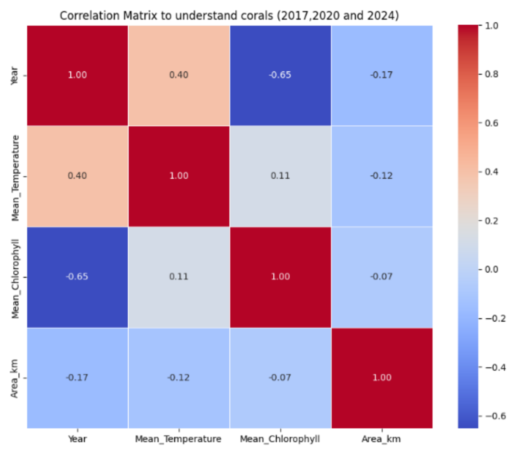


Figure 55 - Correlation Matrix of Island 3

Weak Correlations observed in this area would indicate that other factors could influence the effect of coral bleaching over island 4.

5.5 ISLAND 5

5.5.1 Land Classification

In 2017, the predominant class was shallow water covering 1.6km^2 shown in figure 56, accounting for approximately 73% of the total area. Deep water covers 0.13km^2 at 6% and Sand covers 4.2% of the area. From Figure 58, a noticeable change in Deep water which succeeded with 0.13km^2, covering 6% was observed. Sand represented 4% at 0.09km^2. Coral reefs constituted 0.36km^2 at 16% of the total area where, the bleaching areas were comprised of Light and Medium bleaching at 0.2km^2 (11%) and 5% (0.1km^2) respectively. The island showed no presence of strong coral bleaching.

By 2020, the land classification changed which showed a decrease in the Sand Category that covered 1.3% of the total area at 0.08km^2. Shallow water covered 1km^2 representing 16% of the area (Figure 57) along with deep water showing the largest coverage at 4.5km^2 accounting for 70%. The coral coverage decreased to 0.7km^2 at 12% of the area that highlighted light bleaching areas as the most extensive category covering 0.5km^2 covering around 8.5% of the area, followed by medium bleaching at 0.12km^2 at 1.87% and the appearance of strong bleaching at 1.6% at 0.1km^2 of the total area.

In 2024, shallow water covered 0.8km^2, accounting for 37% of the total area. Deep water had a higher coverage with 39% at 0.9km^2. Sand accounted for 3.4% of the total area while certain regions could not be calculated and therefore appeared in the No data category at 3.8%. Coral ecosystems stabilized at 16% (Figure 59) with an area of 0.3km^2 but the bleaching levels changed, exponentially, as the strong category covered 0.1km^2 at 5% of the total area whereas Medium bleaching areas recorded 0.09km^2 representing 4% of the region and Light bleaching being the most dominant category covering 7.6% accounting for 0.17km^2 of the area.

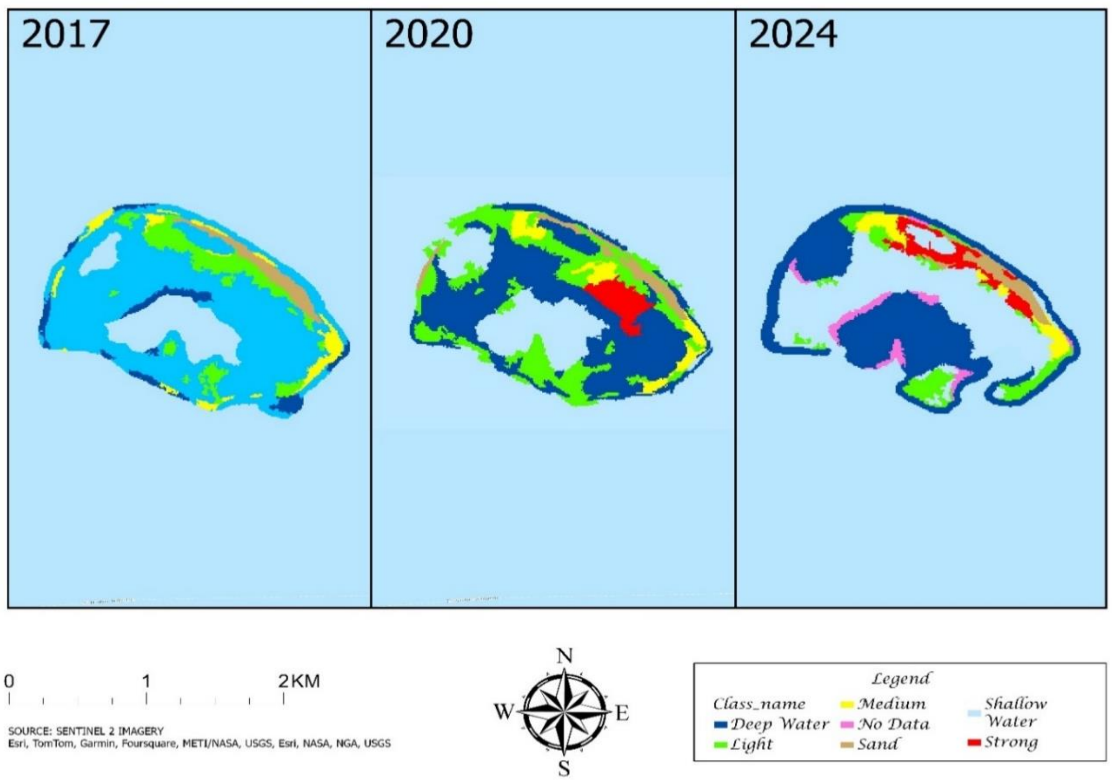


Figure 56 - Land Classification of Island 5 from 2017 to 2024

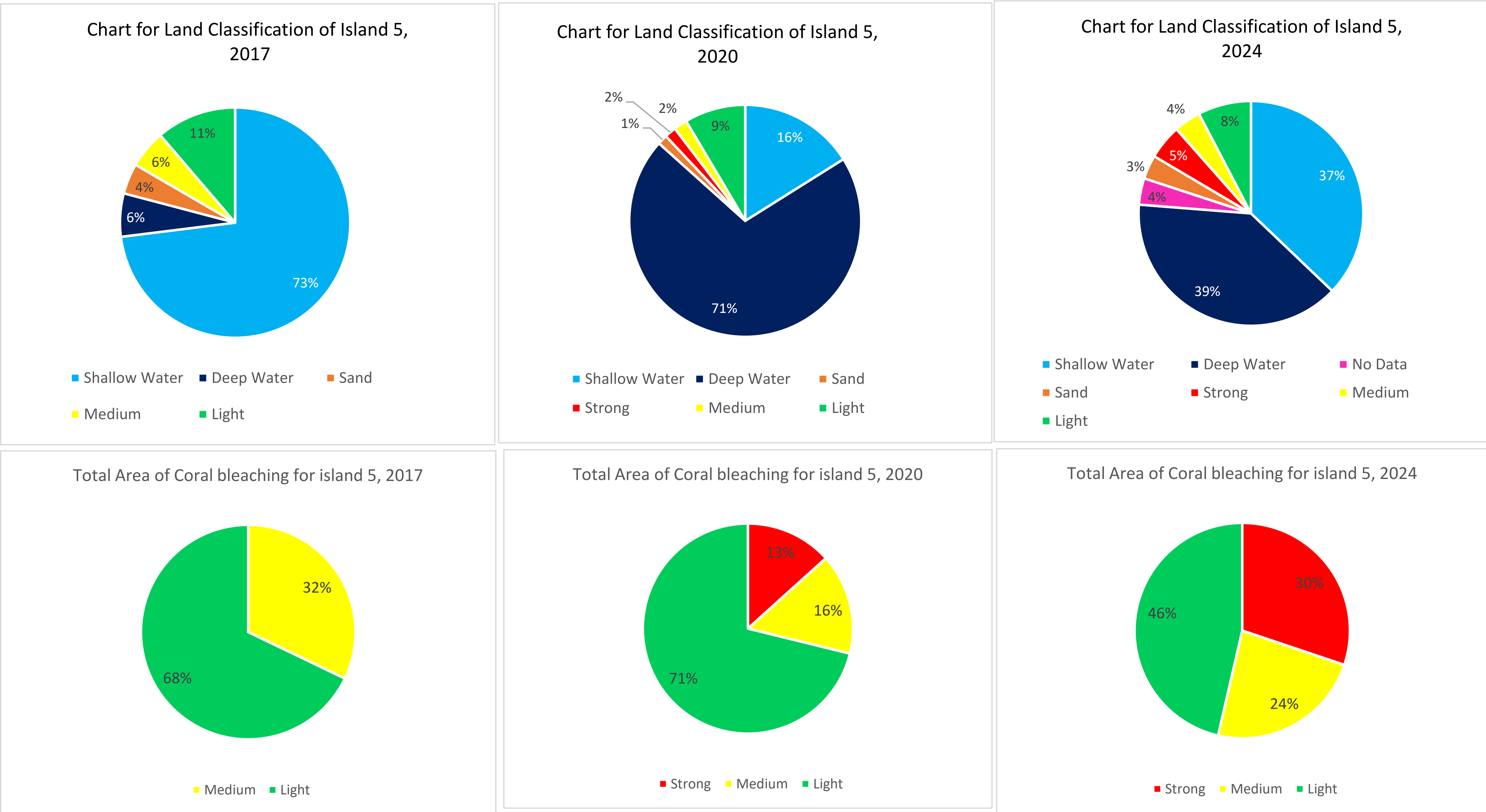


Figure 57 - Land classification and distribution of coral bleaching for island 5 from 2017 to 2024

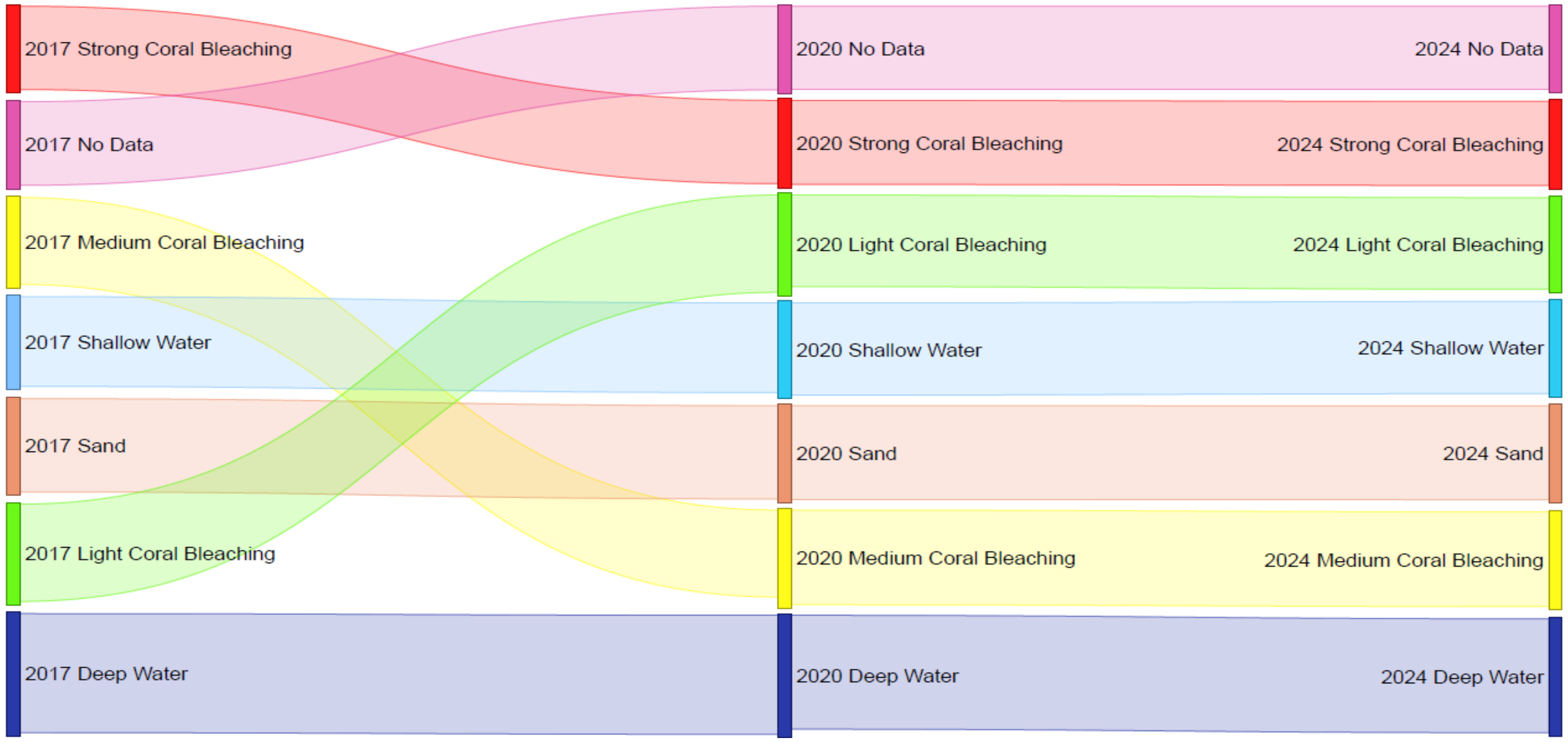


Figure 58 - Sankey Graph showing the transition of land classification from 2017 to 2024 for island 5

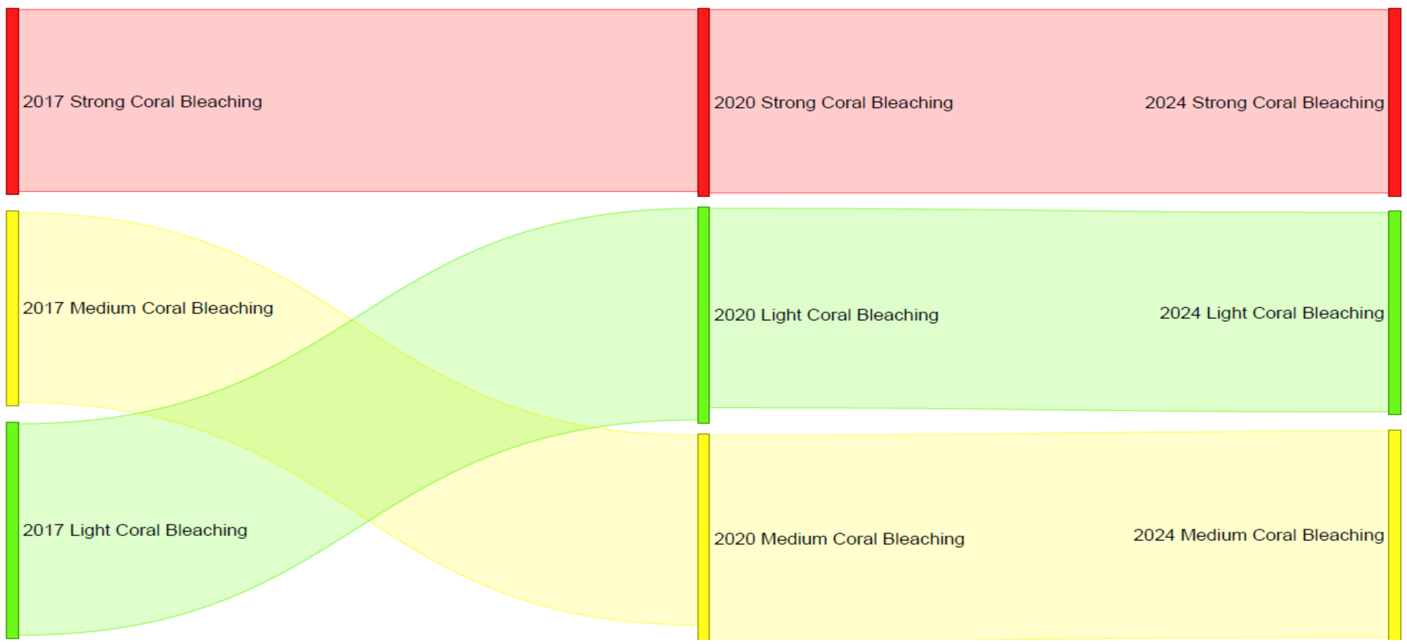


Figure 59 - Sankey Graph showing the Coral bleaching Distribution of Island 5 from 2017 to 2024

5.5.2 Trend Study for Bleached areas

This island displayed varied trends in coral bleaching and chlorophyll levels. The chlorophyll content seen in figure 61, decreased significantly from 2017 to 2024 in light bleached areas by 0.24 mg/m^3. The total chlorophyll content increased from 2017 to 2020 but decreased by 2024 for all the areas within the island. Bleached areas (figure 62) along with the chlorophyll content showed an increase from 2017 to 2020 indicating deteriorating conditions with regards to coral health. Increase in temperature could be the cause of coral bleaching but does not directly affect chlorophyll levels.

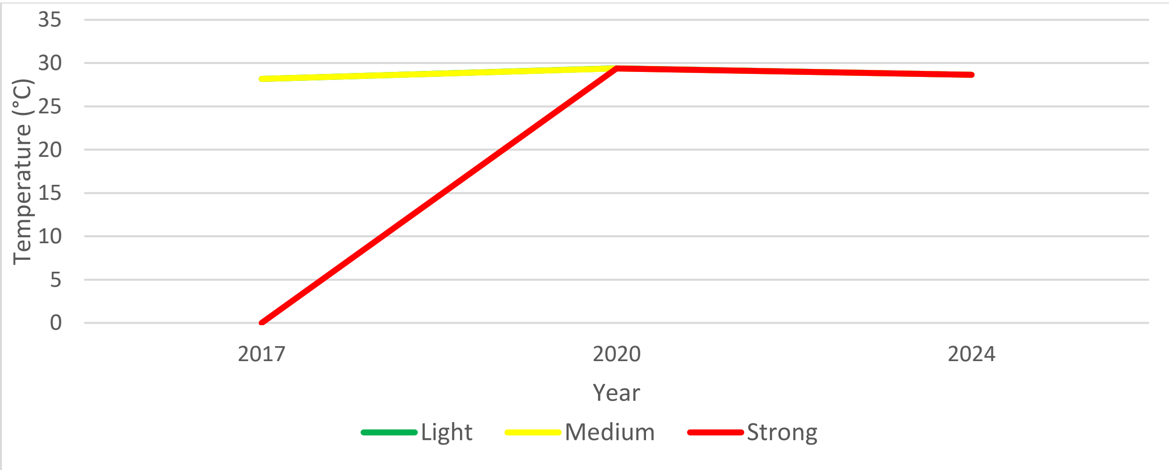


Figure 60 - Mean Temperature (°C) Trend for Island 5 by coral bleaching categories

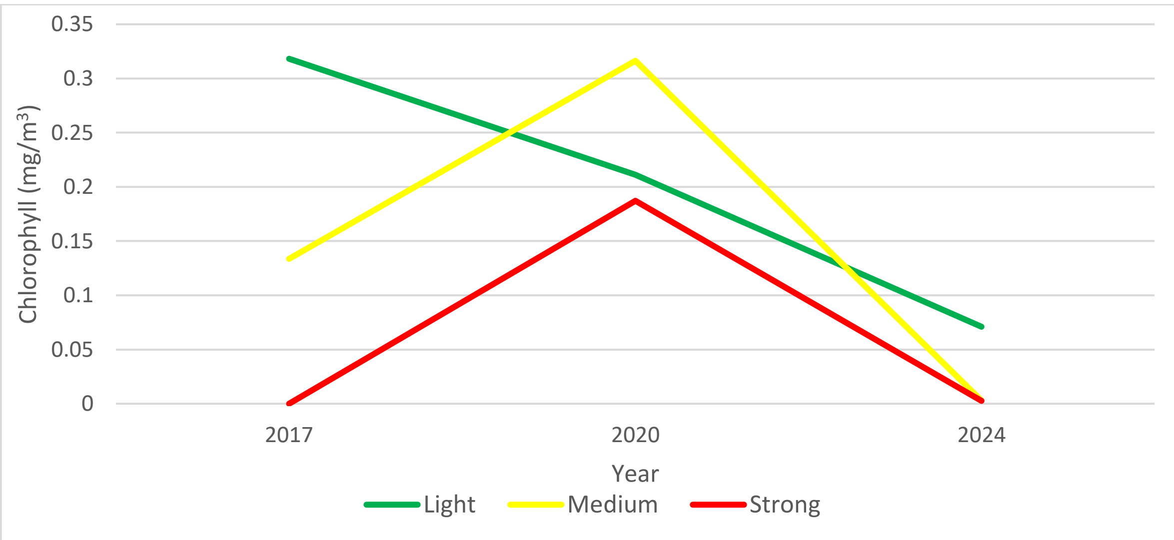


Figure 61 - Mean Chlorophyll (mg/m^3) Trend for Island 5 by coral bleaching categories

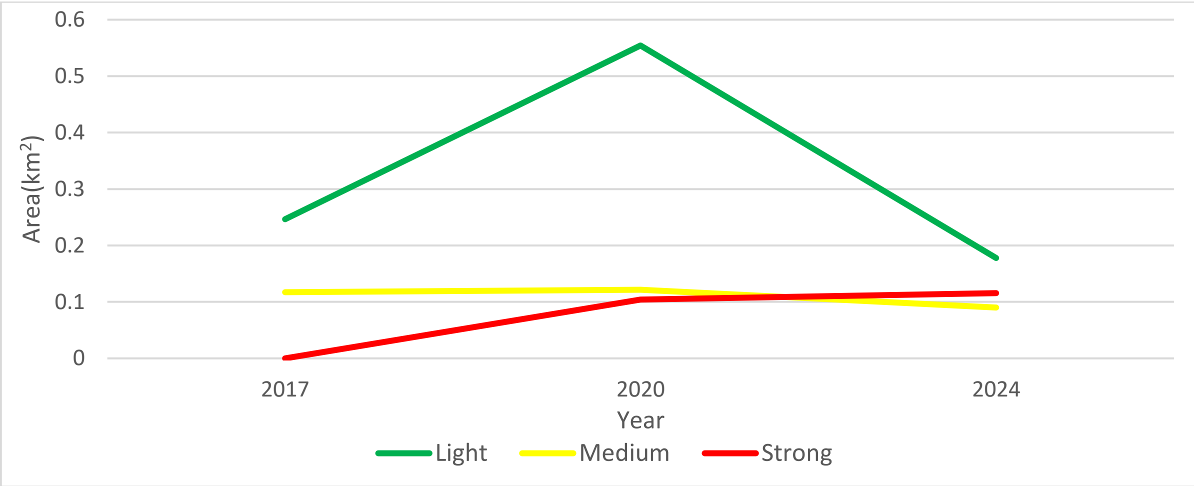


Figure 62 - Mean Area (km^2) Trend for Island 5 by coral bleaching categories

5.5.3 Correlation Matrix of bleached areas

Correlation of Mean Temperature with Mean Chlorophyll

There is a weak positive correlation of 0.24 indicating that as the temperature changes, the chlorophyll levels tend to vaguely increase.

Correlation of Mean Temperature with Bleached Areas

A weak positive correlation of 0.29 could imply that increase in temperatures could affect the coral bleaching trends by causing it to change values thereby shifting the bleaching to another category of severity.

Correlation of Mean Chlorophyll with Bleached Areas.

A moderate positive correlation of 0.33 could indicate that higher chlorophyll levels are associated with larger areas being affected by coral bleaching.

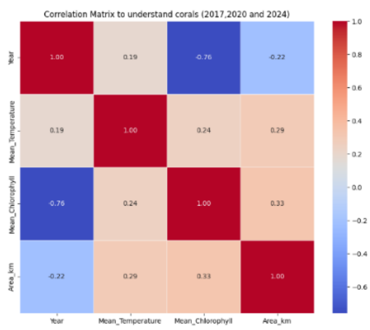


Figure 63 - Correlation Matrix of Island 5

6. Discussion

This study shows a generalized increase in coral bleaching across all the islands. From the research conducted by Xu et al, the data obtained was calculated by the reflection of each band of the sentinel 2 sensor. Unlike that study, the results obtained here were classified by ArcGIS Pro and then tabulated which proved to be successful. Island 1 showed substantial changes in land classification and bleaching patterns due to the large coverage of the region. By 2024, medium bleaching areas showed a decline and shifted to the severely bleached regions. Island 3 showed higher chlorophyll levels in light bleached areas and increased by 2024 which could prove less bleaching. The transition from light to medium bleached areas from 2020 to 2024 indicates the variation in bleaching severity with medium bleaching becoming more predominant. With the help of Correlation figures, we can comprehend the relation between temperature chlorophyll and bleaching areas. Island 3 showed weak positive correlation that could explain the direct impact of temperature on chlorophyll concentrations, contrary to the weak negative correlation between chlorophyll and bleached areas that could be inferred as higher chlorophyll levels could be associated with bleached areas emphasising the complex relation between all these variables.

7. Conclusion

Through this venture, we understand the critical impact of environmental changes on the coral ecosystems in the Maldives. A significant increase in coral bleaching from light to medium and strong categories along with the changing variability in temperature and chlorophyll levels, contributed to the ever-increasing stress on coral reefs.

It should also be noted that this comprehensive undertaking was done with the sole purpose of finding a method to study coral bleaching using remote sensing rather than classifying the data. We can conclude that this method worked as the output data was studied with the variation in temperature and chlorophyll levels, which yielded positive coral bleaching results.

In conclusion, the data showed an urgent need for conservation and preservation of coral reefs to prevent the collapse of an entire food chain and the endangerment of certain species that depend on these reefs for their survival. The insights from this research can guide policy and management to better protect these species and maintain these ecosystems. The use of remote sensing over large and often isolated areas provided a valuable methodology for future coral reef studies.

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8.1 Applications Used For The Project

- ArcGIS Pro
- SNAP (Sentinel Application Program)
- Biblioshiny (R studios)
- Python
- Microsoft Office suite
- Imagery: Sentinel 2, Sentinel 3 and Landsat 8
- Microsoft BI